PB83-107474

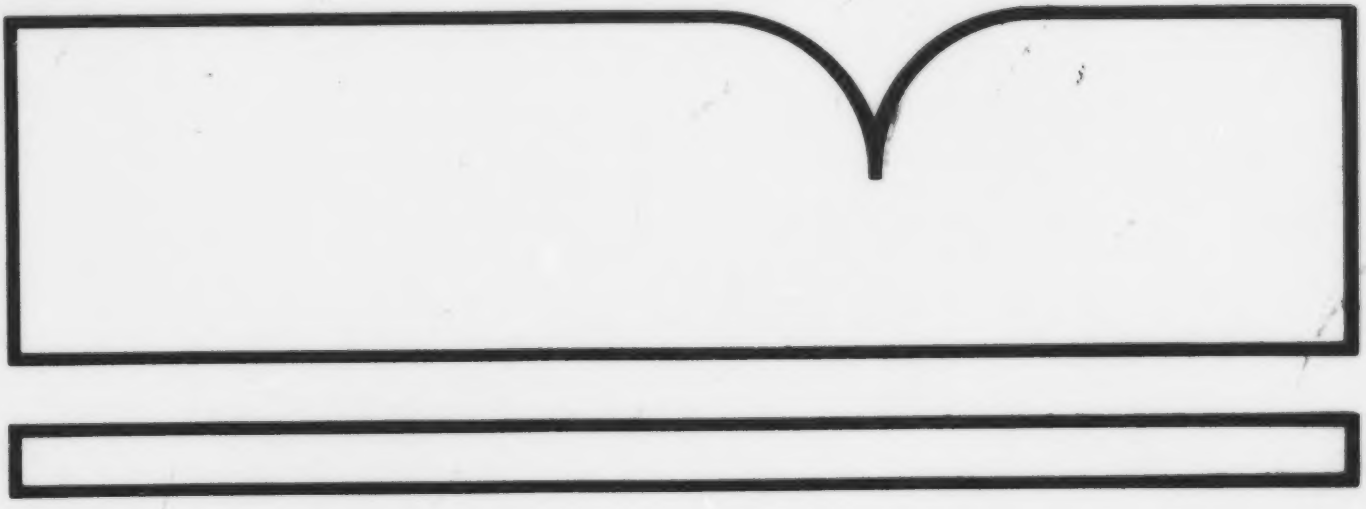
A Pneumatic Conveying Test Rig for Municipal Solid Waste Fractions

National Center for Resource Recovery, Inc.
Washington, DC

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Sep 82



U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/2-82-083
September 1982

PB83-107474

A PNEUMATIC CONVEYING TEST RIG FOR MUNICIPAL SOLID WASTE FRACTIONS

by

Marc L. Renard
National Center for Resource Recovery, Inc.
Washington, D.C. 20036

Grant No. R806709

Project Officer

Carlton C. Wiles
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-82-083		PB83 107474

4. TITLE AND SUBTITLE	5. REPORT DATE
A PNEUMATIC CONVEYING TEST RIG FOR MUNICIPAL SOLID WASTE FRACTIONS	September 1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Marc L. Renard	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
National Center for Resource Recovery, Inc. 1211 Connecticut Avenue Washington, DC 20036	11. CONTRACT/GRANT NO. R806709
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory-Cinti, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Carlton C. Wiles (513) 684-7871

16. ABSTRACT

This report analyzes the material properties and system parameters relevant to the pneumatic conveying of municipal solid waste and its processed fractions. Comparisons are made with the conveying of conventional industrial feedstocks, and a rationale for sizing and specification of a pneumatic conveying test rig is developed. The test assembly is to be used at solids rates ranging from a few to 20 to 30 Mg/h, on materials such as shredded municipal solid waste, refuse-derived fuel, canstock, etc., to study the dependency of the operating parameters and conditions on the conveying velocity, solids-to-air ratio, and product characteristics. Cost and sizing of the conveying test rig is established from this analysis and from manufacturers' quotes. Tradeoffs between outright purchase and testing for a fee are examined.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
		13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	72
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

NOTICE

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This publication evaluates a pneumatic conveying rig in which municipal solid waste and its processed fractions are to be tested experimentally. The approach and suggested procedures should be of interest to designers and operators of municipal waste processing plants.

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

ABSTRACT

This report analyzes the material properties and system parameters relevant to the pneumatic conveying of municipal solid waste and its processed fractions. Comparisons are made with the conveying of conventional industrial feedstocks, and a rationale for the sizing and specification of a pneumatic conveying test rig is developed. The test assembly is to be used at solids rates ranging from a few to 20 to 30 Mg/h, on materials such as shredded municipal solid waste, refuse-derived fuel, canstock, etc. to study the dependency of the operating parameters and conditions on the conveying velocity, solids-to-air ratio, and product characteristics. Cost and sizing of the conveying test rig is established from this analysis and from manufacturers' quotes. Tradeoffs between outright purchase and testing for a fee are examined.

This report was submitted in fulfillment of Grant No. R806709 by the National Center for Resource Recovery, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period June 1979 to October 1980.

9 1/8"
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables vii
Acknowledgments viii

1. Introduction 1
   Objectives 1
   Approach 2
   Results 2
2. Considerations in the Pneumatic Conveying of Municipal Solid Waste Fractions 4
   Definitions and ideal design conditions 4
   Advantages and disadvantages or limitations . . 7
   Material characterization 8
3. Materials Considered for Pneumatic Conveying . . . 15
4. Rationale for the Design of a Test Rig 18
   Intended function 18
   Design parameters 19
   Pneumatic conveyor test rig specifications . . 43
   Summary and conclusions 53

References 54
Appendices

A. Pneumatic conveying of MSW fractions: typical operating parameters at sample U.S. facilities 57
B. Sample letter 61
C. Alphabetical list of equipment manufacturers contacted during this investigation 62

FIGURES

Number		Page
1	Resource recovery system schematic	5
2	Schematic view of pressure circuit	11
3	Histogram for angle of repose and apparent density for 45 pneumatically conveyable materials and comparison with MSW fractions	14
4	Graphical extrapolation of Madison's curves, recommended conveying velocity versus particle diameter, D_p, and material bulk density, ρ_b	22
5	Cross-plot of conveying velocity versus particle size for given bulk density	23
6	Types of pneumatic conveying systems	27
7	Dynamic (velocity) pressure versus velocity	31
8	Air inlet pressure loss versus velocity . . .	32
9	Number of duct diameters for one velocity pressure loss versus velocity	33
10	Pressure loss per unit length versus velocity (straight runs)	34
11	Pressure loss per unit length versus duct diameter	35
12	Pressure loss in elbows versus duct diameter	37
13	Pneumatic test rig. Passive Circuit. Schematic view	41
14	Schematic of solids flow rate and circuit hold-up determination by feed stoppage	49

TABLES

Number		Page
1	Properties of Pneumatically Conveyed Material	9
2	Mohs' Scale of Relative Hardness	12
3	List of Materials to be Conveyed, with Sampled Properties	16
4	Conveying Velocities of Various Materials	20
5	Example of Test Durations for RDF at Various Solids-To-Air Ratios	29
6	Properties of Materials to be Conveyed	44
7	Summary of Manufacturers' Quotes	51

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

ACKNOWLEDGMENTS

Thanks are due to K. Sterret and F. Gerchow (Sprout-Waldron, Koppers Co.), G. Huber (Ohio Blow Pipe Co.), J.C. Delpex and J. André (Neu Co.) for their cooperation in providing information on conveying equipment and systems. We are also grateful to Jay Campbell of NCRR for helpful technical comments, and to Kenneth Niemann of NCRR for obtaining most of the data on U.S. facilities in Appendix A1.

BEGIN LAST LINE OF TEXT

EPA Form 2350-6 (4-80)
(PREVIOUSLY CIM 250.6, EPA FORM 1371)
TYPING GUIDE SHEET

SECTION 1

INTRODUCTION

This report investigates the parameters, design, and cost of a full-scale laboratory rig in which a variety of feedstocks from municipal solid waste (MSW) are pneumatically transported and tested for conveyability. The aims are to relate in an organized manner the material characteristics, pneumatic system geometry, and air and solids flows, thereby guiding the choice of a test assembly and providing a technical basis for forthcoming experimental measurements.

OBJECTIVES

The objectives of this study were:

- To critically analyze conveying of fractions of MSW instead of more conventional, homogeneous industrial or food feedstocks.
- To determine which of the properties of these materials might be considerably important to pneumatic conveying.
- To analyze the parameters or physical variables involved in such conveying.
- To examine the materials likely to be most easily, efficiencly, and economically conveyed in pneumatic systems.
- To develop meaningful information on the conveyability of actual feedstock.
- To provide a rationale for the design of a pneumatic conveying test rig based on engineering evaluation, calculations, or rules of good practice.
- To define cost brackets for test rigs in relation to their performance and capabilities in handling various MSW fractions.

APPROACH

The approach taken in meeting these objectives was:

(a) To relate measured material properties (as described in Part I of this Contract Report) to those of more conventional industrial products being pneumatically conveyed, using references to the existing published literature or information furnished by equipment manufacturers.

(b) To select a representative list of four materials -- shredded MSW, refuse-derived fuel (RDF), heavy fraction, and ferrous fraction -- some or all of which could be tested in a proposed pneumatic conveying test rig.

(c) To define, based on engineering practice and calculation procedures, the parameters of a test circuit and associated equipment (for example, it could convey, during a batch test of a few minutes, an RDF-type of material at solids flow rates of 2.0 to 20.0 Mg/h).

(d) To use the information and data developed in (b) and (c) to request and analyze vendor quotes (equipment and price) for the proposed pneumatic conveying test rig.

(e) To outline a proposed experimental plan using this assembly to study operating characteristics in pneumatic conveying as a function of the feedstock, solids mass flow rate, and air-conveying velocity.

RESULTS

The study critically reviewed material properties and system parameters important to the pneumatic conveying of solid waste fractions. Four materials conveyable or potentially conveyable by pneumatic methods were selected and analyzed. A rationale for the design of a pneumatic conveying test rig using actual feedstocks was developed, and procedures were indicated for the determination of projected system size and pressure requirements. Based on these specifications, quotes from equipment vendors were solicited and reviewed. The options proposed by manufacturers for this assembly were found to be in good agreement with an in-house evaluation, and their relative merits were analyzed.

Information or guidelines developed during this evaluation should be useful to specification engineers or equipment vendors dealing with new applications of pneumatic conveying to heterogeneous and variable feedstocks from municipal solid waste.

SECTION 2

CONSIDERATIONS IN THE PNEUMATIC CONVEYING OF MUNICIPAL SOLID WASTE FRACTIONS

DEFINITIONS AND IDEAL DESIGN CONDITIONS

Pneumatic conveying is a method by which a material flow of similar or dissimilar particles (such as grain) or objects (such as plastic bottles) is created by suspending and carrying the solids in an air flow. This air circulates in a duct of appropriately large dimension, at a speed sufficient to pick up, propel and prevent later settling of, the solids being transported.

In its simplest terms, the definition of a pneumatic conveyor system for a specific application requires:

(a) a study of

- the geometry of the proposed circuit (straight runs, elbows, risers, etc.).
- the pressure drop (vacuum or positive pressure) and amount of air required.
- the dimensioning (diameter or equivalent diameter) of the ducts.

(b) a choice of components (blower, drive, valves, cyclones, etc.), based on engineering requirements and cost.

(c) a test plan to assure, during assembly and start-up that the system as set up meets its operational requirements.

In the case of pneumatic conveying in resource recovery systems, it should be kept in mind that, within the "total system" schematized in Figure 1, conveying is integrated to -- and in fact the bloodstream of -- a much larger network of inputs, outputs and unit operations. Wide variations in product size, characteristics and throughputs are likely to be the rule, rather than the exception.

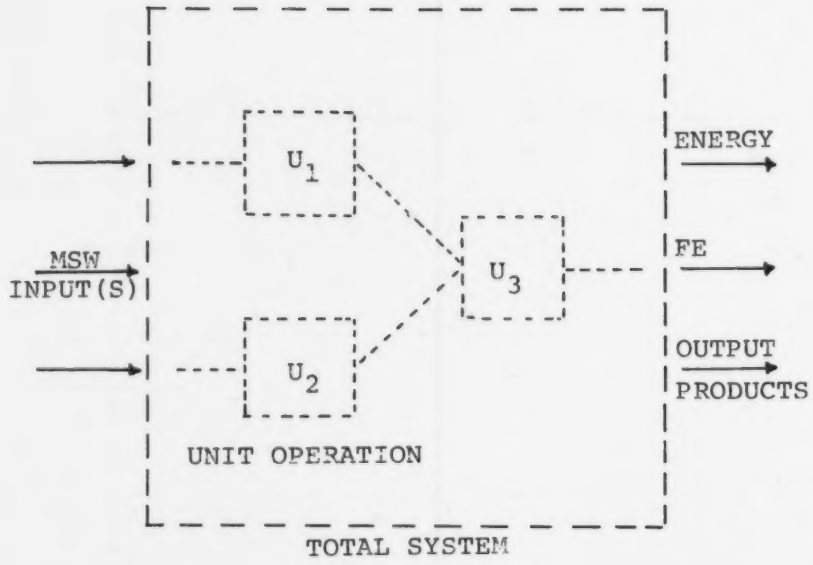


Figure 1. Resource recovery system schematic.

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

Practitioners in the field would label as ideal the following set of conditions, in designing a pneumatic conveyor (1):

(1) the feedstock is homogeneous, has been previously handled and is well known, not overly abrasive or corrosive.

(2) the conveying fluid is air at ambient temperature.

(3) the lengths of ducting, air and solids or mass flow rates are within previously explored normal ranges.

(4) no difficult constraints exist on the siting and sizing of equipment.

(5) transport is from one pick-up or injection point (A) to one arrival or end point (B) (Figure 2).

The present work deals with the definition of a pneumatic test rig, or equivalently the use of existing manufacturers' test rigs at plant sites, to develop meaningful information for the design of such conveying systems in resource recovery applications. From this viewpoint of the above conditions for an "ideal" situation, #2 (air at ambient temperature), #4 (siting and sizing), and #5 (one starting point, one end point) can reasonably be met.

However, as will be seen in more detail below, even the "best" fractions from processed municipal solid waste (MSW) are to a large degree inhomogeneous in size, shape and composition of the particles, at any one time, and furthermore variable over time. To expect to meet condition #1 is thus unrealistic. Rather, one should attempt to convey variable, inhomogeneous mixtures for which changes in properties or dimensions are tolerable. This might be shown with some confidence in preliminary demonstrations or tests, or by analogy with products deemed to be "somewhat" similar, such as air-classified light fraction (RDF) and shredded paper trim.

By the same token, the limited amount of technically documented, published experience in the pneumatic conveying of waste fractions from MSW (2,3), and the reported unfamiliarity of equipment manufacturers with these feedstocks, presently would not allow that the feedstocks to be considered "well known" (#1). "Normal" ranges for circuit lengths and air flow rates can only be surmised from an extremely sparse base of data.

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

EPA-287 (Cin.)
(4-76)

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD BEGIN SECTIONS HERE

ADVANTAGES AND DISADVANTAGES OR LIMITATIONS

According to P. Descamps and G. Jodlowski (1), possible advantages and disadvantages of the pneumatic conveying "option" in industrial applications could be listed as follows:

Advantages	Disadvantages or Limitations
(†) - Low labor requirements	(*) - Material moist or sticky
(†) - Low dust levels	- Size or density of particles requires excessive conveying speeds, leading to:
(†) - Low or zero spillage and materials loss	(*) High power consumption
(†) - Compactness of equipment in an existing building	(*) High abrasion
- Ease of matching to existing configurations	(*)[a] Fragile materials, the size or shape of which should not change
(?) - Low maintenance requirements	- High temperature of materials incompatible with equipment used
- Safety	- Diameter of particles D_p "too large" (taken to mean: Diameter of the duct, $D_D \leq 3\ D_p$)
- No contamination of materials	(*) - Excessive power required, W_s (taken to mean: $W_s \geq 7 \times 10^{-3}$ kWh/Mg, hour and horizontal meter)
- No bags, drums or containers	(*) - High cost of equipment (and/or replacement) for abrasive materials
(?) - Continuous operation	
- Ease of automatic process control	
- Can handle materials at high temperature	
- Possible to transport in an inert atmosphere	
- Large-scale storage and handling is possible	
(†) - Low space requirements	
- Relatively lower add-on costs for higher throughputs	

As should be expected, not all of the factors listed will apply or be of significance to MSW and its processed fractions. Daggers have been used by us in the list to designate "expected" advantages in the left column; interrogation marks to show areas

(a) d-RDF pellets for example

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.) (4-76)

of strong doubt (based on the limited experience), and stars to point to limitations or areas of concern in conveying MSW fractions.

Although any precise balance between the pluses and minuses, in the above list, would be meaningless, it is apparent that, with only one exception, all disadvantages or limitations exist to a considerable degree in the pneumatic conveying of MSW fractions. Of all possible advantages, only the most immediately obvious apply, such as low labor, low dust, no spillage, relative compactness. Yet, a considerable number of them are of no importance, and serious questions - some based on several years of testing and operating experience - remain regarding high wear, reliable continuous operation and high maintenance (4,5).

Thus, a decision to use a pneumatic process for handling MSW fractions should be very carefully weighed and based on all theoretical, laboratory, or full-scale information that can be obtained at the definition and design stage.

MATERIAL CHARACTERIZATION

A number of principal properties and characteristics of the material to be pneumatically conveyed are of fundamental importance in the design or testing of the system. Others might be less critical, but still of interest in assessing conveyability and might be called auxiliary. Finally, other elements of information might be given to characterize properties in storage, in use, or in later operations. An example of breakdown between material properties is given in Table 1, after Reference (6).

Upon inspection, it would appear that principal properties P1 through P5 should indeed all be needed in characterizing a waste fraction.

P1. Could consist of a partly quantitative, partly qualitative description of the components and "make-up" of the fraction. For example: weight distribution by component (possibly broken down in class sizes), moisture content, particle shapes or appearance (for example: single or double sheets of shredded newspaper), etc. Qualifiers could be added, such as "stringy," "fibrous," "sand-like," etc.

P2. A shaker screen analysis of particle size distribution should be performed, in accordance with a standard sieving analysis procedure, such as defined by the American Society for the Testing of Materials (ASTM). However, in a number of waste fractions (trommel oversize, RDF), the largest number of particles are pliable, thin flakes or pieces of paper and plastic sheets.

TABLE 1. PROPERTIES OF PNEUMATICALLY CONVEYED MATERIAL

Principal	Auxiliary	Others
P1. Nature of material	A1. Temperature (if $\neq T_{ambient}$)	0.1 Later use
P2. Particle size distribution (PSD)	A2. Moisture (if stocky)	0.2 Tendency to arch or bridge
P3. Abrasivity	A3. Fragility	0.3 Material (true density)
P4. Bulk (apparent) density	A4. Corrosiveness	
P5. Angle of repose	A5. Dimension of largest lump	
	A6. Special precautions	
	A7. Danger of explosions	

After: P. Descamps, G. Jodlowski (6)

Other factors are, therefore, of importance, besides the screen analysis "linear dimension" of the particles, for example, the "aspect ratio" (length/width) and "length-to-thickness ratio" (flatness) of flaky elements. Such elements have been studied to some extent in a previous NCRR report (6). For "conventional" products being pneumatically conveyed, results of the particle size analysis have a bearing on

- the determination, or educated guess (by analogy to a similar material), of the required conveying velocity.
- the minimum allowable diameter of the conveying ducts. The rule of thumb is that, to avoid clogging and plugs, the diameter of the duct,

D_D, should be no less than three times the "dimension" of the particle, D_P (7).

$$D_D \geq 3\ D_P$$

Note, however, that for a pliable (paper trim) or early cut material (thin aluminum canstock trim), the above condition is construed to apply to the width rather than the length of the strip. Furthermore, practitioners in the industry often recommend, for fibrous substances, that the minimum duct diameter be higher than a set threshold value, related to the fibrous material more than to the size of the particles. This criterion is used to prevent packing and matting of the materials which could agglomerate the fibers and result in obstructions. For example, the criterion for shredded straw is said to be (8)

$$D_D \geq 0.250 \text{ m } (10 \text{ in.})$$

- the need for dust control at the exhaust of the cyclone or solids separator (Figure 2).

P3. Abrasivity

The materials are often conveyed at speeds on the order of 25-30 m/s (5,000 to 6,000 ft/min). W. Courtney even reported that at the Chicago S.W. plant, the original conveying speeds, for RDF containing some glass (a few percent), were as high as 37 m/s (7,200 ft/min) (2). Extremely severe abrasion, on the order of 50% of the 6.3 mm thick, mild steel wall, was reported at some locations on the wall of the conveying duct after less than 50,000 Mg of RDF conveying. Another detailed study of RDF pneumatic conveying at the St. Louis plant was performed by Murphy et al (3). Abrasion, particularly at elbows, was due to glass particles present in the material, and was found to be very intense, resulting in some cases in holes through the thickness of the metal or liner. Again, a rule of good practice is to attempt, as much as possible, to choose a wall material "harder" than the abrasive particle (or reduce, to the extent possible, the qualities of abrasive materials). A guide for this choice is the Mohs' scale of relative hardness (Table 2).

In this table, it can be seen that glass has a higher index than steel. Hard liners (cast iron, basalt) or wearable one (rubber) could be required in sections where high speed particles are in contact with the walls (elbows). Also, air velocities, V, should be kept at a reasonably low value since mass removal by abrasion is expected to increase with a power of V on the order of 3 (9,10).

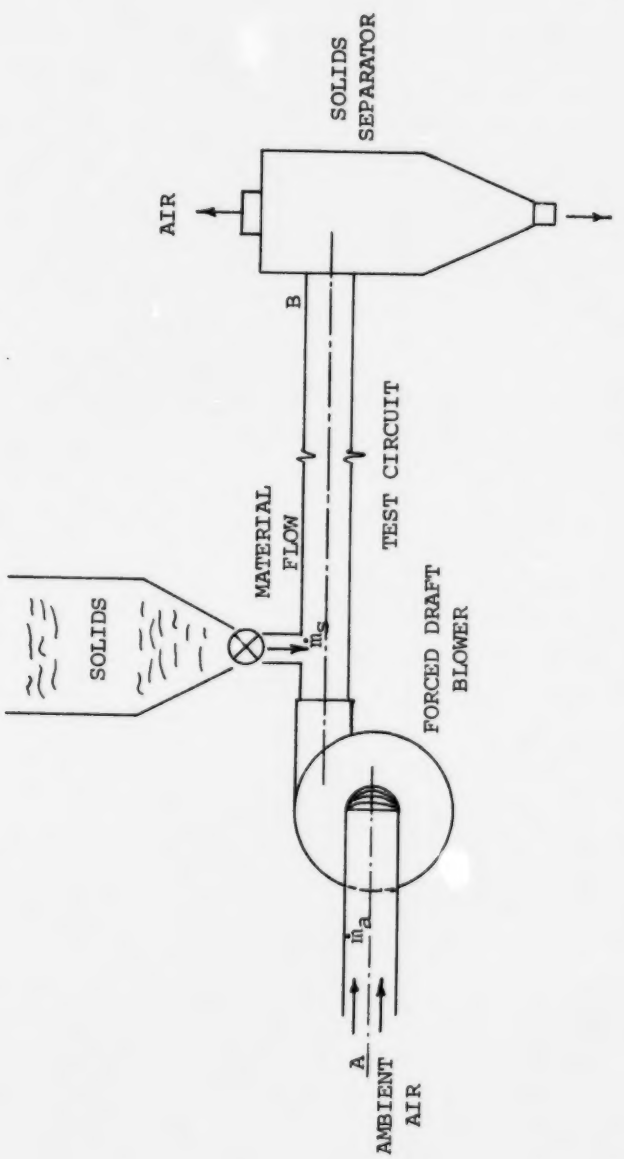


Figure 2. Schematic view of pressure circuit.

TABLE 2. MOHS' SCALE OF RELATIVE HARDNESS

Reference material and value of index		Index of conveyed materials	
Gypsum, salt	1	Anthracite	2.4
Talc	2	Calcium carbonate	4
Calcite	3	Steel	5-5.5
Fluorine	4	Cast iron	6
Apatite	5		
Feldspar, glass	6		
Quartz	7		
Emerald	8		
Coryndon	9		
Diamond	10		

P4. Bulk (or apparent) density

The apparent (or bulk) density, or bulk density, can be measured in accordance with an ASTM standard, as explained in Appendix A of Part I of this Contract Report (11,12). A distinction was made, and experimental differences were obtained, between the compacted (or standard) bulk density, and the loose bulk density. The former is essentially measured by determining the mass of material contained in a reference cubic volume, after tapping, whereas the latter is determined on a "free standing" conical pile "poured" on a horizontal floor.

In pneumatic conveying applications for MSW fractions, it could be argued that the material is stored and fed (for example, through a hopper/rotary valve assembly) into the circuit in the "compacted" form, so that the value of the compacted bulk density should apply.

However, in many cases of homogeneous materials, such as powders, the bulk density, easily determined experimentally, is only used to estimate the (possibly unknown) true density of the

material. Indeed, for "similar" powders in a non-compressed state, ε, the fraction of voids in a unit volume, is generally known from previous practice. (It ranges from 0.3 to 0.6 for powders.) The apparent bulk density, ρ_b, and material density, ρ_s, are related to the air (or interstitial fluid) density ρ_g by

$$\rho_b = \varepsilon \rho_g + (1 - \varepsilon) \rho_s$$

Typically, for most MSW components, $\rho_s \geq 1000$ kg/m^3, so that $\rho_g/\rho_s \simeq 10^{-3}$. If $\varepsilon \lesssim 0.95$, or $\rho_b \gtrsim 3$ lb/ft^3, the following simplification holds, within 2%:

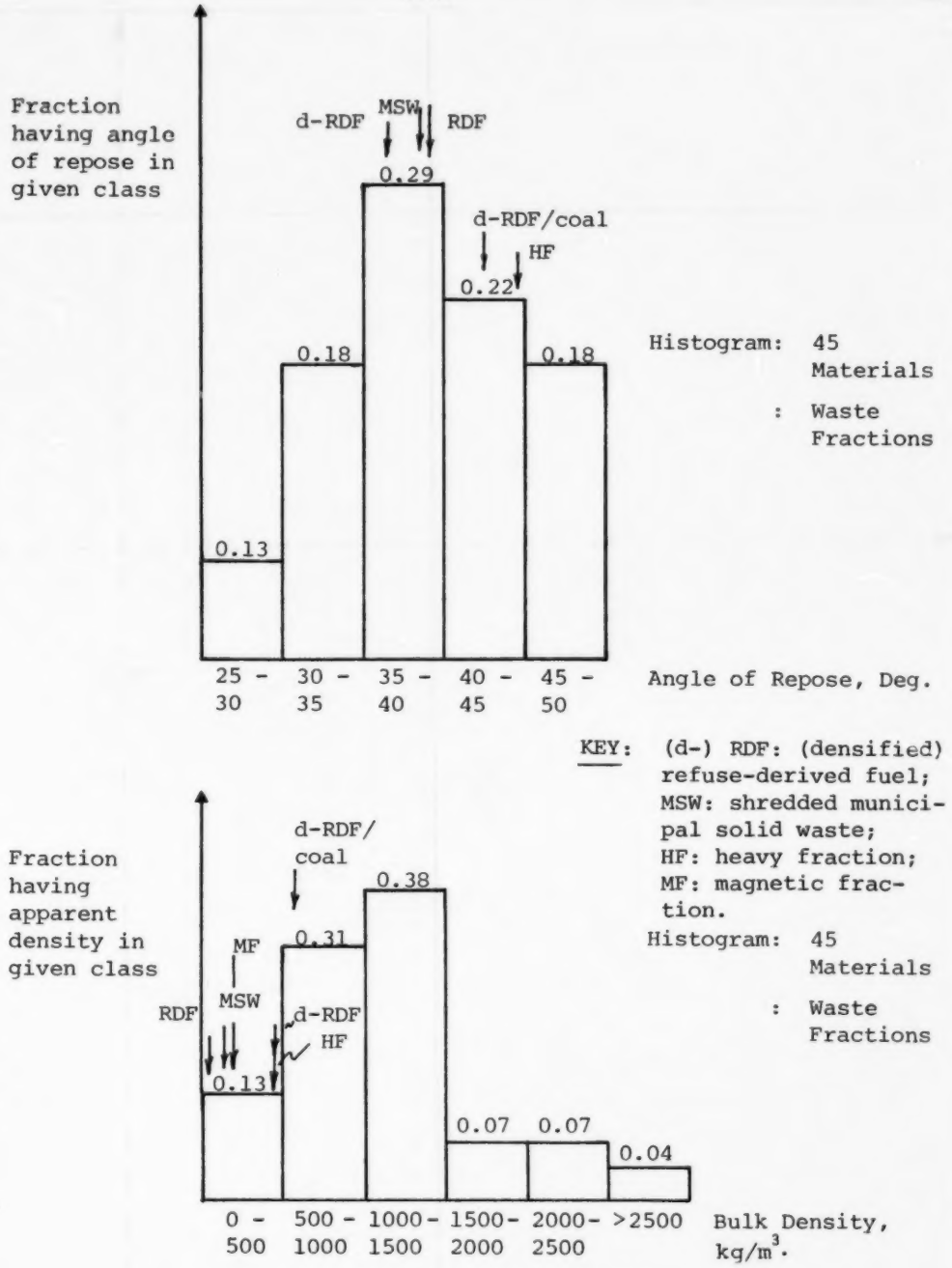
$$\rho_b \simeq (1 - \varepsilon) \rho_s$$

Hence ρ_b is a measure of ρ_s, knowing ε, or of ε, knowing ρ_s.

P5. The angle of repose has been defined in the first part of this report and measured values for selected fractions from MSW were reported. These will not be repeated here, and the reader is referred to the first part of the investigation (11, 12).

It might be of interest, however, to see where, as regards their angle of repose (mean values in Table 4, Ref. (11)), the five waste fractions fit in a set of "pneumatically conveyable" materials listed by P. Descamps and G. Jodlowski (10). From these authors' data, on 45 materials, from cement to ground glass, we plotted a histogram (on a percent basis) giving the relative frequency of materials having an angle of repose in a given class (Figure 3). It is seen that average values of the angles for the waste fractions from MSW are in the "central" region of the histogram. Granulated coke, for example, has an angle of repose of 40°, and fines of mica span the range 30° to 45° (average 37.5°).

For completeness, it should be noted that all five fractions are definitely toward the very low or low end of the apparent (bulk) density histogram for the 45 materials considered (Figure 3).



Original Data on 45 Materials: Ref. 10.

Figure 3. Histogram for angle of repose and apparent density for 45 pneumatically conveyable materials and comparison with MSW fractions.

SECTION 3

MATERIALS CONSIDERED FOR PNEUMATIC CONVEYING

The waste fractions originally considered in this discussion are the same as in the "solids conveying" part of this report (Part I) (2), namely:

- shredded waste (SW)
- ferrous fraction (MF)
- heavy fraction (HF)
- RDF, fluff (RDF)

d-RDF pellet conveying would defeat the purpose of densification by generating fines and attrition and is not examined below.

It might be noted that raw waste is not in this list, and this point warrants some discussion. The particle size distribution of raw municipal waste has been studied by, among others, Winkler and Wilson (13), Ruf (14), Trezek (15). It is seen from these data that a few weight percent of textiles, paper and cardboard, and possibly metals are of a (sieve) size larger than 25 cm (10 in.). All other practical considerations aside, the "duct size" criterion alone would dictate that the conveying pipe for such material to be sized at 75 cm (30 in.) diameter. At a typical conveying velocity of 28 m/s (5,500 FPM), a total pressure drop of 10 k Pa (40 in. W.G.) generated with a mechanical efficiency of 50% would require approximately 250 kW (330 HP) of installed fan power, hardly within the scale of a small pneumatic test rig! Not surprisingly, one example of full-scale pneumatic conveying system for raw, although somewhat sized waste, given in the literature (16) is that of Sundeberg, Stockholm, Sweden, which requires five turbo-extractors of 100 kW each. These extractors create at the inlets to the vacuum circuit a negative pressure of approximately one-half atmosphere, in order to collect, remove and pneumatically convey solid waste from a complex of apartment houses.

The four above-mentioned fractions have the particle size distribution represented in Figure 3 above, and tabulated below (Table 3), along with the measured moisture (wt%, as-received), bulk density and angle of slide. It is seen that both moisture and bulk density for the four fractions span one decimal order

TABLE 3. LIST OF MATERIALS TO BE CONVEYED, WITH SAMPLED PROPERTIES.

	RDF (1)	Shredded MSW (2)	HF (3)	Ferrous Fraction (4)
Moisture, Volume (Range) % as recd.	10.4 (10-20)	29.7 (20-30)	20 (15-20)	2.6 (2-3)
Bulk Density Compact kg/m^3 (lb/cft)	37.3 (2.33)	125.3 (7.83)	334.7 (20.92)	193.5 (12.1)
Angle Slide,° (on steel plate)	31	29.3	27.5	18
Component Description	Paper, plastics, light fabrics.	Paper, metals, glass, plastics.	Glass, cans (Fe, Al), cardboard, textiles, rubber, wood.	Steel cans, pieces of steel.
Particle Size Distribution (wt % - mm (in.))				
102 (4)	-	4.1	1.2	28 (< 150 mm (6"))
+76, -102 (+3, -4)	-	7.1	0.8	26
+51, -76 (+2, -3)	0.6	12.1	12.5	36
+25, -51 (+1, -2)	4.8	12.3	23.4	9
+13, -25 (+½, -1)	57.8	15.7	18.0	0
+6, -13 (+¼, -½)	21.3	17.6	20.2	1
+6 mesh, -6 (+6 mesh, -¼)	5.4	12.3	14.1	[0
-6 mesh	10.1	18.8	9.8	

of magnitude, approximately. Similarly, specific gravities of materials should be expected to vary from 0.8 (newsprint) to 7.2 (ferrous). The angle of slide, 18° for the ferrous fraction (FF) and much larger (about 30°) for the three others (SW, RDF, HF), reflects the fact that metal on metal friction should be lower than that of paper flakes, wood or rubber on metal.

In view of these wide ranging differences in relevant physical properties, it should be foreseen that a pneumatic conveying test rig designed for one, or possibly two of the above waste fractions might not be suitable, even after slight modifications, for the other materials listed. Aware of such limitations, when requesting quotes for budget and equipment list from qualified manufacturers, we left it to the vendor to comment on the applicability of their proposed assembly to several fractions of waste. However, as exemplified in Appendix A1, RDF and possibly shredded MSW are the only materials which in actual U.S. resource recovery practice are conveyed in full-scale installations. Accordingly, the following order of priority in choosing the system was indicated to the manufacturer: the system should be able to handle material (1), RDF, as a first priority; then (2) shredded MSW; then (3), ferrous fraction; then (4), heavy fraction.

For two of these materials (magnetic fraction, heavy fraction), due to either the relatively high bulk density (HF and MF), or absence of fines (MF), there appears to be no really strong incentive to convey these fractions pneumatically rather than by other than mechanical solids conveyors. (Parameters and material characteristics affecting the mechanical conveyability of these fractions are discussed in Part I of this report.) Shredded MSW, as described in Table 3, is seen as representative of a coarse (primary shredded) fuel product, if magnetic metals are assumed removed. Therefore, the ensuing discussion of design parameters for the rig will be focused on an RDF- (or possibly shredded MSW) like material such as described by (1) or (2) in Table 3.

SECTION 4

RATIONALE FOR THE DESIGN OF A TEST RIG

INTENDED FUNCTION

Our purpose is to evaluate components and design parameters for a test rig on which a series of pneumatic conveying experiments and tests would be conducted. The goal of this experimental program is to gain insight into, and develop numerical data and document operation on, the pneumatic conveying of selected fractions of waste.

Physical measurements or observations would relate to:

- the required transport velocities (minimum or "safe operating").

- the pressure drop per unit length (or duct diameter) experienced in ducting or circuit elements such as: straight, horizontal or vertical runs; 90° elbows in soft bends (radius of curvature 5 to 8 duct diameters); vacuum scoops; solids separators (cyclone or other inertial devices); dust control filters, as required.

- the fan or blower operating characteristics (speed, air flow, pressure, efficiency, power consumption).

- a qualitative description of plug-free operation, tackiness, effect of moisture; and abrasivity, to the extent the latter is observable in tests of relatively short durations.

It is foreseen that the test rig would include two transparent, impact-resistant removable plastic or glass sections for flow visualization by high speed photography. One of these test sections would be straight, the other would be a 90° elbow.

DESIGN PARAMETERS

As previously explained, the test rig design parameters will be evaluated on the assumption that the material to be conveyed is a fluff RDF, as exemplified by material (1) in Table 3, or possibly a coarse, shredded MSW listed in the same table as material (2). The possible use of the rig for other types of materials (such as (3) and (4) in Table 3) should be looked at as an added benefit, not a primary design criterion.

With varying degrees of specificity, the engineering approach to sizing and calculation of pneumatic conveying systems for homogeneous (grain), or relatively homogeneous (wood chips) feedstocks has been examined by a number of authors (14-15, 17-22). The fundamental aspects of suspended solids flow, from a theoretical and experimental viewpoint, have been examined extensively and in depth by Soo (23) and his co-workers. The reader is referred to Soo's book, in reference, for a list of papers and reports on this topic.

Worthy of note, these sources do not deal with a strongly heterogeneous mixture such as municipal waste fraction, and the main emphasis is put on powders or materials which are from tens of microns to 2 or 3 mm in size. Very little is said on the transport of disparate mixtures mostly composed of particles of size 10 mm and up. A notable exception is the experience gained in the conveying of paper trim and similar thin, "strip-like" waste (24).

Therefore, it was our view that published guidelines on circuit sizing and component selection should be used with an added measure of caution, and that confirmation of assumptions made below might only be obtained as a result of a testing program to be conducted with the rig.

Conveying Velocity

A list of conveying velocities said to be "commonly accepted" by industry practitioners was given by Jorgensen (25) and is reproduced in Table 4.

These velocities, which are those of the conveying air, are given without reference to particle size or shape, other than the implicit assumption that being those normally encountered in feedstock, product or waste conveying.

The relative velocity of the conveyed particle, V_{rel}, with respect to the conveying air, V_a (or velocity slip), in a horizontal pipe, could be, according to Jorgensen (25) computed by the formula developed in the early (1924) work of Gasterstadt (26):

TABLE 4. CONVEYING VELOCITIES OF VARIOUS MATERIALS

Material	m/s (fpm)
Castor beans	25.4 (5000)
Cement	35.6 (7000)
Coal, powdered	20.3 (4000)
Cork, ground	15.3 (3000)
Corn	28.5 (5000
Cotton	22.9 (4500)
Iron oxide	33.0 (5500)
Knots, blocks	25.4 (5000)
Limestone, pulverized	25.4 (5000)
Oats	22.9 (4500)
Paper	25.4 (5000)
Rags	22.9 (4500)
Rubber	22.9 (4500)
Salt	28.0 (5500)
Sand	35.6 (7000)
Sawdust, dry	15.3 (3000)
Shavings	17.8 (3500)
Wheat	29.5 (5800)
Wool	25.4 (5000)
Vegetable pulp, dry	22.9 (4500)

From: Ref. (25)

$$V_{rel} = V_T\ (0.18 + 1.28 \times 10^{-2}\ V_a) \quad \text{(velocities in m/s)} \qquad [1]$$

The terminal velocity, V_T, is itself calculated as

$$V_T = \left(\frac{2g}{C_D}\ \frac{\rho_p}{\rho_a}\ \frac{p}{A_{eff}}\right)^{1/2} \qquad [2]$$

ρ_p, p, A_{eff}, C_D are the specific mass, volume, effective cross-section and drag coefficient of the particle, respectively; and ρ_a is the specific mass of air.

The reduction in cross-section for the air flow due to the presence of solid particles can be neglected in the range of solids (to air) ratios, SR (kg solids/kg air) investigated here. Taking SR = 10 as an absolute upper limit of the range (see below), the error thus made would be on the order of

$$\varepsilon = \frac{\mathcal{V}_{solids}}{\mathcal{V}_{gas}} = \frac{m_{solids}}{m_{gas}}\ \frac{\rho_{gas}}{\rho_{solids}}$$

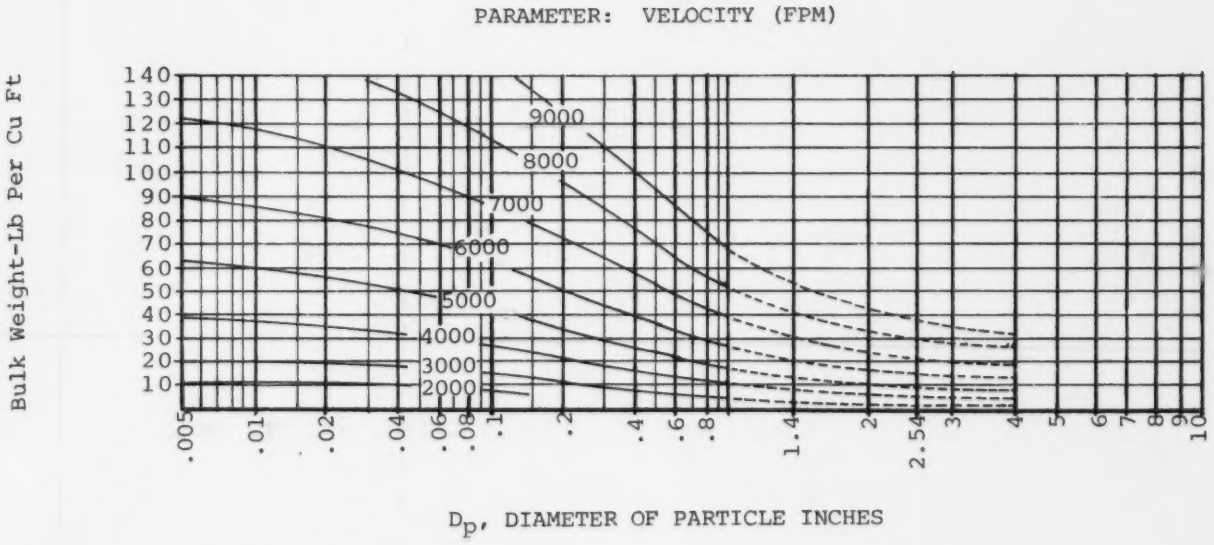
Since ρ_{gas}/ρ_{solids} is typically on the order of 10^{-3} ($\rho_{air} = 1.2$ kg/m^3; $\rho_{solids} \simeq 1000$ kg/m^3), $\varepsilon \leq 10^{-2}$.

Assuming a relationship between bulk density and material velocity, Madison (25) developed a chart relating recommended bulk density to particle size (or unspecified shape), for a given conveying velocity (Figure 4). No data are given for particle sizes larger than 25 mm (1 in.), but extrapolation might be possible for a first estimate.

In Figure 5, a cross-plot of Madison's curves shows the increase in conveying velocity, V_a, with particle size (up to 25 mm), for a given bulk density; and the increase in V_a with bulk density, for a given particle size.

For the purpose of preliminary design, the "safe conveying" velocity can be selected based on one of the three (not necessarily independent) considerations:

A. By analogy to homogeneous materials. The paper content in RDF is expected to be high, in excess of 70% in most cases (27,28), and this predominant fraction consists mostly of newsprint. Therefore, it would appear reasonable to select, from Table 4, the conveying velocity for paper, namely 25.4 m/s (5000 FPM). Other unpublished industrial data this author consulted indeed appear to recommend 25 m/s (4920 FPM) as a safe conveying velocity for discrete pieces of waste trim (paper, cardboard) having a mass per unit surface lower than 0.45 kg/m^2 (92 lb/10^3 ft^2). For a piece made of newsprint and 51 x 51 mm in size (2 x 2 in.), this would correspond to



From: Madison (25)
Extrapolated for $D_p \geq 254$ mm (1 inch)

Figure 4. Graphical extrapolation of Madison's curves, recommended conveying velocity versus particle diameter, D_p, and material bulk density, ρ_b.

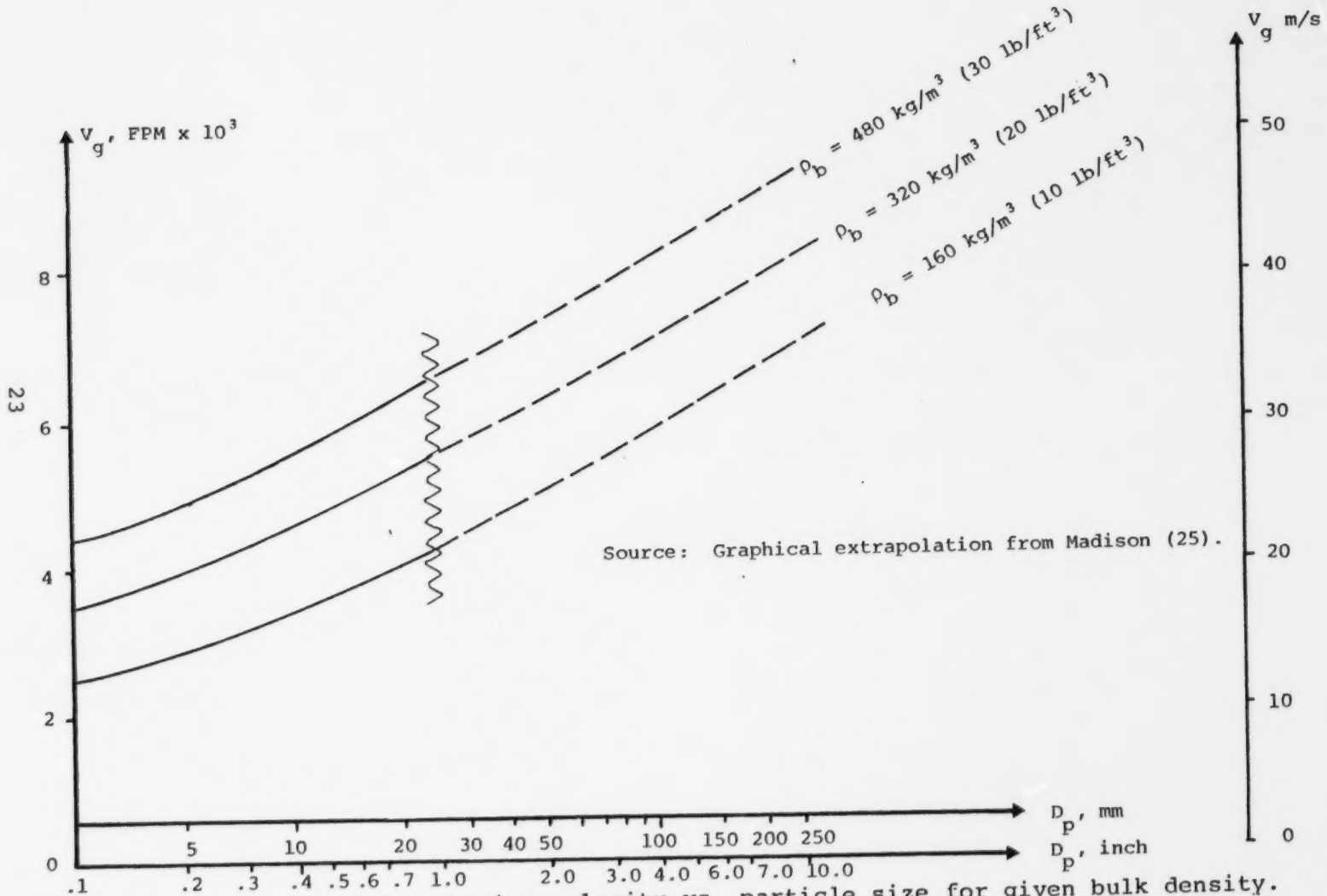


Figure 5. Cross-plot of conveying velocity vs. particle size for given bulk density.

approximately eight thicknesses of newsprint sheet (0.0635 mm per sheet). Due to their higher relative thickness and bulk density (368 kg/m^3 (23 lb/ft^3)), wood chips might require a somewhat higher value, on the order of 30.0 m/s (5900 FPM). Gerchow, speaking about normally conveyed products or wastes, notes that for some 90% of conveying situations, a 5000-FPM velocity is adequate (29). He further points, however, that for products for which the particle size is greater than 1/8-in.[3], the minimum velocity must be estimated or determined by tests (29).

A method suggested in the same reference for estimating minimum velocities is to use an equation expressing the balance of weight and pressure on the frontal end of the particle, or with the same notations as above

$$V_{min} = \left(\frac{\rho_p g \mathcal{V}_p}{1/2\ \rho_a A_{p,eff}}\right)^{1/2}$$

This is equivalent to setting $C_D = 1.00$ in the equation.

As examples, the following values are computed:

- flake of newsprint, 0.1 m x 0.1 m, one sheet thick (t_p = 0.0635 mm), ρ_p = 820 kg/m^3, $A_{p,eff} = 10^{-2}$ m^2; V_{min} = 9.3 m/s (1830 FPM),
- particle of corrugated board, 0.1 m x 0.1 m, thickness = 0.0033 m, ρ_p = 270 kg/m^3, $A_{p,eff} = 10^{-2}$ m^2; V_{min} = 12.1 m/s (2375 FPM).

These minimum velocities should only be used as a level of reference to indicate how wide the margin of safety is on the average conveying velocity (between the pickup and discharge values), and to allow for safe operation without plugging, excessive drifting and progressive buildup of solid masses on the walls, in elbows, etc.

On the basis of this discussion, a probable, acceptable range of operating velocities would be 28.0 to 30.5 m/s (5500 to 6000 FPM). The upper limit could be raised somewhat if the feedstock is expected to contain heavier particles (metals) of given size, or if the duct diameter is relatively small compared to the largest particle size.

B. On the basis of bulk density (Madison's curves, graphically extrapolated), using data in Table 3 (particle size distribution, bulk density) on the assumption that all materials are sized at 10.2 cm (4 in.) maximum (including MF, the ferrous fraction), the safe conveying velocities range from

$V_a \simeq 15.2$ m/s (2000 FPM) for $\rho_b = 37$ kg/m^3 (2.33 lb/ft^3)

to

$V_a \simeq 34.6$ m/s (6800 FPM) for $\rho_b = 335$ kg/m (21lb/ft^3)

The graphically extrapolated values should not be expected to be more than rough estimates, since they lack in experimental basis and graphical accuracy.

C. On the basis of presently existing facilities conveying RDF (Appendix A) and more particularly Courtney's experiments (2), V_a ranges, for circuits varying in length from 42.7 m (140 ft) to 518.5 m (1700 ft) from 26.4 m/s (5200 FPM) to 35.1 m/s (6900 FPM). After reduction to a common length* of 91.5 m (300 ft) (estimated equivalent length of test circuit), these figures would range from 26.4 to 28.0 m/s (5200 FPM to 5500 FPM). These are in good agreement with the above estimate, keeping in mind that in all cases the product conveyed is RDF having a characteristic upper size of from 1.9 cm (3/4 in.) to 10.2 cm (4 in.)

Duct Diameter

Minimum Diameter --

As explained in the beginning of this section, the duct diameter D_D (or equivalent diameter) is selected, for materials of size 1 cm or larger, on the basis

$$D_D \simeq 3\ D_p$$

where D_p is taken to the width of thin strip of material (paper or light metal stock), rather than its length.

For the materials listed in Table 3, for example, and even if the above condition is relaxed, $D_D = 254$ mm (10 in.) would appear as an absolute minimum on the duct diameter.

Choice of Diameter --

The solids-to-air ratio (SR), or kg solid entrained/kg of air, is, as pointed out by Descamps and Jodlowski (22) often determined at the end of the calculations and checked to see if it does not exceed "reasonable" values. A pressure drop is selected first, presumably making allowance for the increase in pressure requirements resulting from the presence of solids. By

---

*This can be done using Gerchow's guidelines (18). If $V_a = 20.3$ m/s (4000 FPM), for a circuit of length L = 61.0 m (200 ft) long, then $V_a = 25.4$ m/s (5000 FPM) if L = 1525.0 m (500 ft); $V_a = 30.5$ m/s (6000 FPM) if L = 305.0 m (1000 ft).

calculation, it is checked that this pressure drop will suffice to maintain as a minimum the safe conveying velocity all along the circuit, given a duct diameter (Figure 6). The air flow rate is known, and the solids flow rate which is conveyable should not, for negative or negative-positive pressure systems (in the -0.5 to +0.1 atmosphere range) exceed that corresponding to a solids ratio of a few units (30). The same authors also point out that SR ≃ 0.3 should be considered a sensible minimum for steady operation. Going any lower in solids concentration would lead to prohibitive volumes and cost of ducts and machinery per unit mass of solids conveyed.

For systems using centrifugal fans as prime movers, some manufacturers use another approach, in which a mean solids-to-air ratio, SR, is chosen as a first approximation using the values below (31).

$\dot{m}_{solids}$ (Mg/h)	0.3	0.4	0.5	1	2 and above
Recommended SR	0.3	0.35	0.4	0.55	0.80

Correspondingly, at a conveying speed of 30.5 m/s (6000 FPM), the air mass and volume flow rate (at ρ_g = 1.2 kg/m^3), and duct diameter would be

$\dot{m}_{solids}$ (Mg/h)	0.3	0.4	0.5	1	>2
$\dot{m}_{air}$ (kg/s)	0.28	0.32	0.35	0.51	0.69
$\dot{Q}_{air}$, m^{3}s (CFM)	0.23 (486)	0.27 (504)	0.29 (617)	0.43 (899)	0.58 (1215)
D_D, cm (in.) for V_g = 30.5 m/s (6000 FPM)	9.8 (3.9)	10.6 (4.2)	11.0 (4.3)	13.4 (4.3)	15.6 (6.1)

From this result, it is seen that in all cases, the above minimum duct diameter condition, based on particle size, will be the determining factor in choosing the duct diameter. To summarize, the duct diameter should be chosen so that $D_D \gtrsim 0.25$ m (10 in.).

Solids-to-Air Ratio

At a nominal rate of solids conveying of 73 Mg/h, the Chicago S.W. plant, according to Courtney (2), would operate at a solids-to-air ratio (for an air flow of 6.81 kg/s (12,000 CFM at 0.075 lb/ft^3)) equal to: SR ≃ 3.0 (kg/solids/kg air). It was mentioned already that SR ≃ 0.3 is in practice the lower end of the economically affordable range. Therefore, it appears sensible to investigate the range (at the design point) $0.3 \lesssim SR \lesssim 3$. Obviously, the test rig operating on air only will give

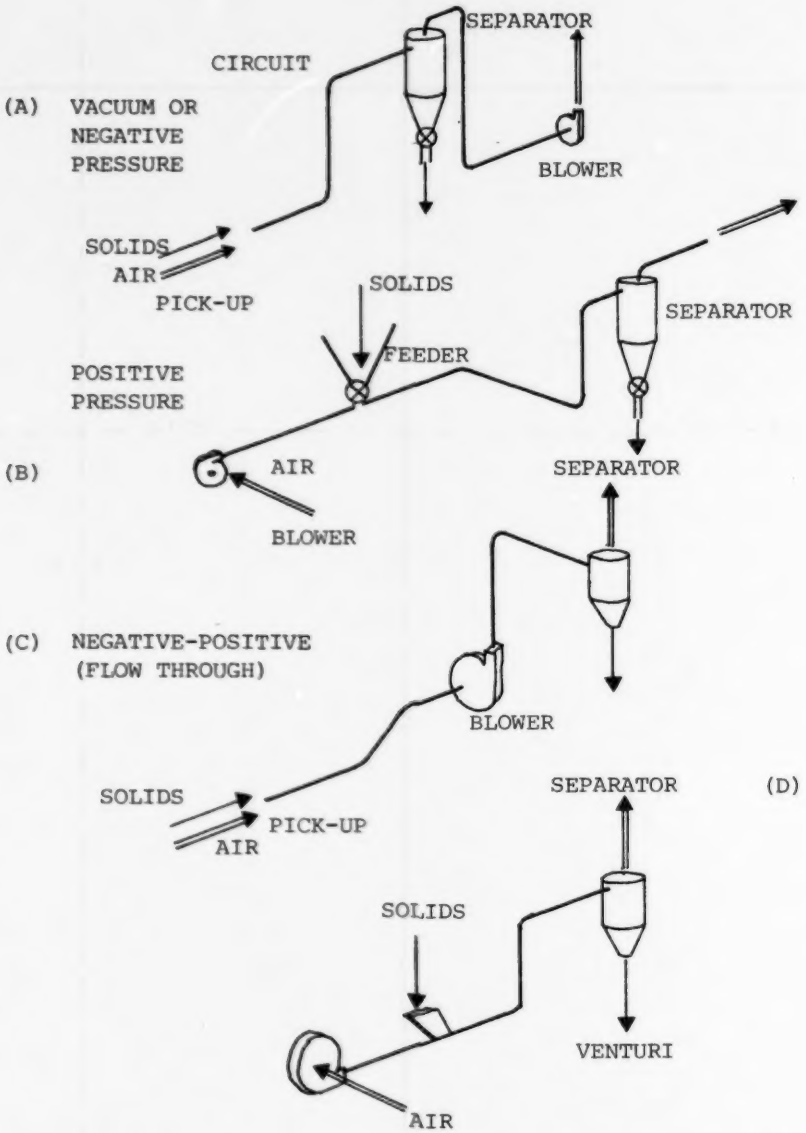


Figure 6. Types of pneumatic conveying systems.

data at a zero solids-to-air ratio, so that the whole range of SR from 0 to 3 can be explored.

Amount and Volume of Material to be Tested

In the estimation of manufacturers consulted, and in our own best judgment, batch tests simulating steady operation on the test rig should have a duration of a few minutes (in no case less than 1 minute) to permit data acquisition.

Whether the tests are conducted at a dedicated facility or at the manufacturers' sites, it was recognized that a batch process, in which a given amount of material is sent through a loop only once during a test,* was preferred for a number of reasons:

- there is no need for materials handling at the solids separation end or for a recirculation loop.

- if the material particle size is reduced by the cutting action of a flow-through materials fan (pull-push system), recirculation would lead to a conveyed product of smaller and smaller particle size. Results might be unrealistic or difficult to interpret.

- this approach is simpler and more economical to implement.

It was also generally agreed that the amount of material and/or volume stored and tested at any one time should not exceed 1 Mg or 10 m^3 (whichever applies first) in order to keep the costs and logistics of collection, freight and handling manageable at laboratory or pilot scale.

Based on these conditions, the example in Table 5 below illustrates the range of test durations and solids-to-air ratio, SR, achievable on a 0.25 m (10 in.) diameter system, operating on an RDF (Material (1) in Table 3) of bulk density ρ_b = 31.3 kg/m^3 (2.33 lb/ft^3).

For denser materials in Table 3, such as shredded MSW, weight (1 Mg max.) rather than volume would be the limiting factor. Assuming that the conveying velocity considered in the example, 30.5 m/s or (6000 FPM), is still adequate, the test durations on one batch would be correspondingly higher due to

*Provision can be made for reuse in the case of negligible physical changes in the feedstock during previous conveying tests.

TABLE 5. EXAMPLE OF TEST DURATIONS FOR RDF AT VARIOUS SOLIDS-TO-AIR RATIOS

Amount tested	373 kg (822 lb) or 10 m^3 (352 ft^3)			
Conveying velocity	30.5 m/s (6000 FPM)			
Volume flow of air	1.55 m /s (3270 CFM)			
Mass flow of air	1.85 kg/s (4.07 lb/s)			
Solids-to-air ratio	0.3	0.5	1	3
$\dot{m}_{solids}$, kg/s	0.56	0.93	1.85	5.56
Flow rate of solids, Mg/h	2.00	3.34	6.67	20.02
Test duration, min	11.2	6.7	3.4	1.1

the larger amount (1 Mg) of material in that batch. (For example, for shredded MSW, from 29.8 min at SR = 0.3 to 3.0 min at SR = 3.0.)

Estimates of Other Design Parameters

Pressure Drop --

In estimating the pressure difference to be developed by the fan or air moving device, the general steps of the procedure recommended by Fischer (17) and Gerchow (18) will be followed. Where useful, an attempt will further be made to corroborate the approach or results with other sources, and to present the data developed here in a more general graphical form. Air is taken to be at ambient density, and pressure corrections should be made in an iterative mode when the first approximation to the pressure drop required has been determined.

In References (17) and (18), the approach taken is to superimpose pressure losses due to the conveying air only, to those attributable to the presence of solids. These two types of losses are now discussed.

A. Air Friction Losses --

A.1 Inlet loss

This pressure differential is required for the pickup of the material particles and losses in the scoop or blower inlet. A first estimate for this loss is 1.24 (18) to 1.5 (32) the dynamic (air velocity) pressure P_d. For ambient conditions (ρ_g = 1 atm, ρ_g = 1.2 kg/m^3), Figure 7 gives the dynamic pressure P_d, as a function of the conveying velocity. Figure 8 is simply the pressure drop, ΔP, corresponding to a well-designed scoop (1.24 P_d pressure loss), again versus conveying speed.

At 30.5 m/s (6000 FPM), the inlet loss is ΔP_{inlet} = 71 mm W.G. (2.8 in. W.G.).

A2. Losses in straight runs

From a cross-plot of Madison and Elliot's friction charts for gases (33) (average pipe), we obtained in Figure 9 curves giving the length, in number of duct diameters, n_ϕ, required for one dynamic (velocity pressure) loss P_d. This is shown over the ranges of interest, 0.10 m (4 in.) < D_D < 0.46 m (18 in.) and 10.2 m/s (2000 FPM) < V_g < 40.7 m/s (8000 FPM).

From these and Figure 7, the graphs in Figure 10 are obtained, giving, for different duct diameters, the pressure loss in mm W.G./30.5 m of duct (in. W.G./100 ft of duct) as a function of the conveying speed. On Figure 11, a cross-plot is made of this pressure loss per unit length as a function of the duct diameter for two speeds: 25.4 m/s (5000 FPM) and 35.6 m/s (7000 FPM).

For V_g = 30.5 m/s (6000 FPM), D_D = 0.25 m (10 in.): n_ϕ = 55 (Figure 9); P_d = 56.9 mm W.G. (2.24 in. W.G.); ΔP/unit length = 4.07 mm W.G./m (4.89 in. W.G./100 ft).

Thus, the estimated pressure drop in four straight runs, each 15.3 m (50 ft) long is for an average pipe:

$$\Delta P = 4 \times 15.3 \times 4.07$$

$$= 249 \text{ mm (9.8 in. W.G.)}$$

However, as noted by Jorgensen (34), in the interest of reducing friction losses, drifting and plugging, smoother pipe with fewer joints is usually used in conveying systems. A correction for smoothness should be applied to the pressure loss. This correction can be found in Jorgensen's book (35). For smooth pipe, a duct diameter of 0.25 m (10 in.) and a velocity of 30.5 m/s

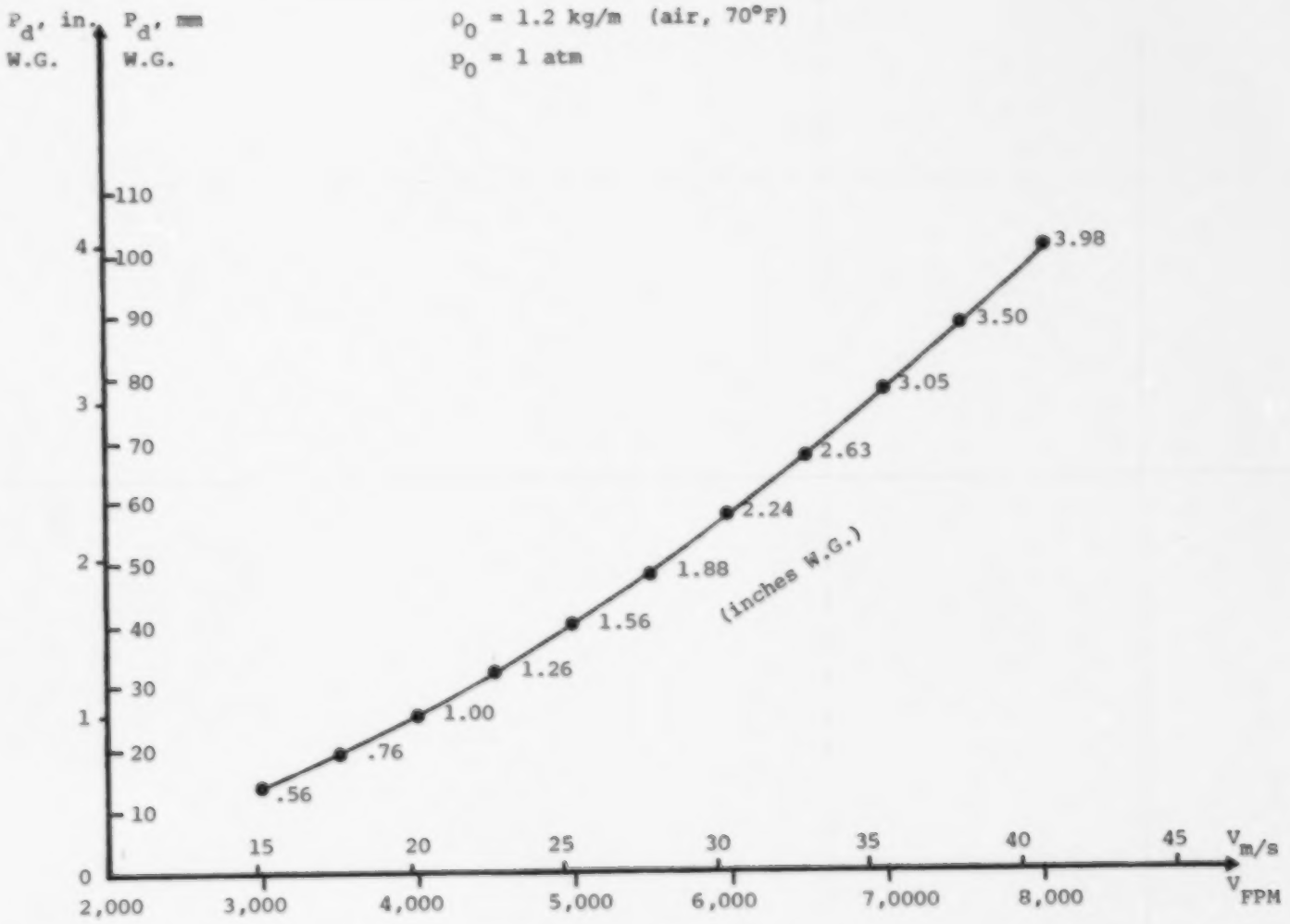


Figure 7. Dynamic (velocity) pressure versus velocity.

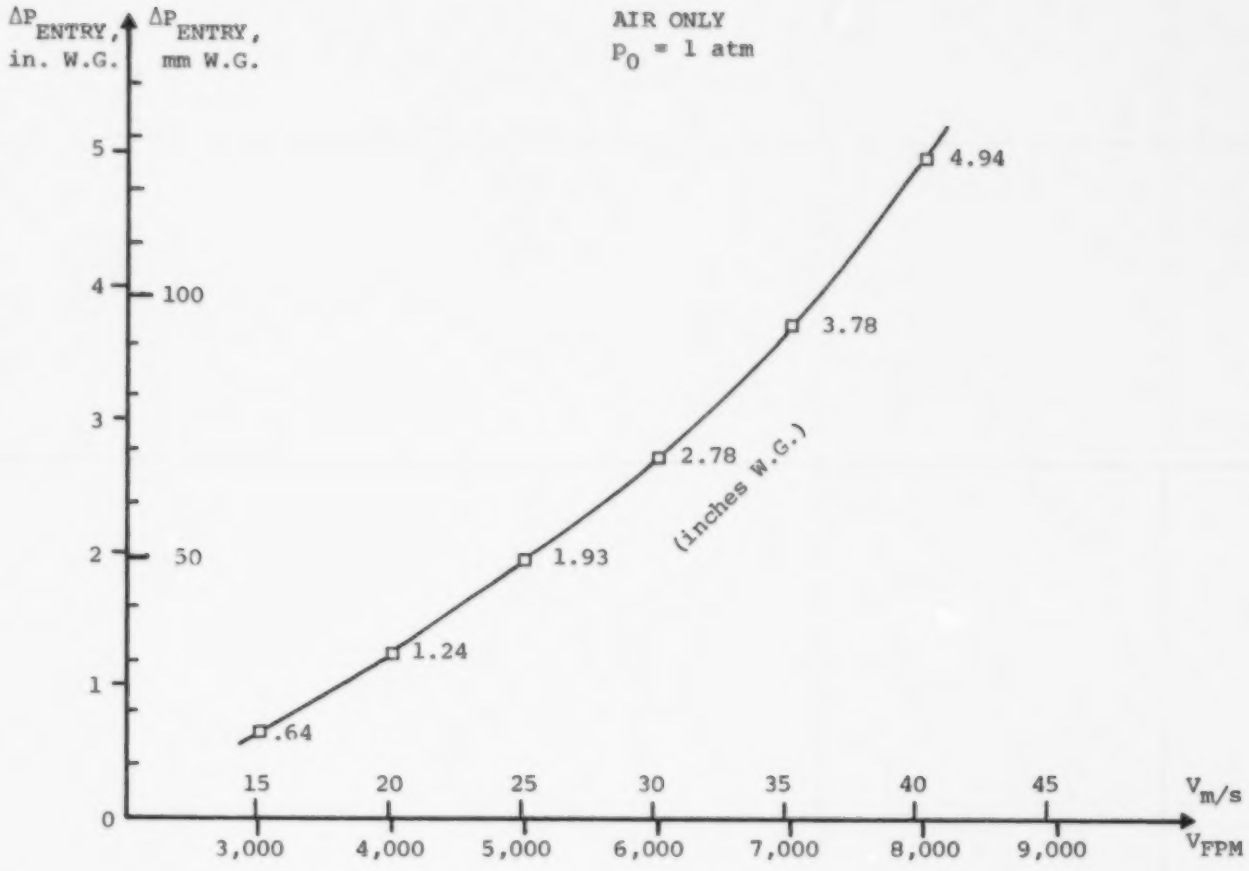


Figure 8. Air inlet pressure loss versus velocity.

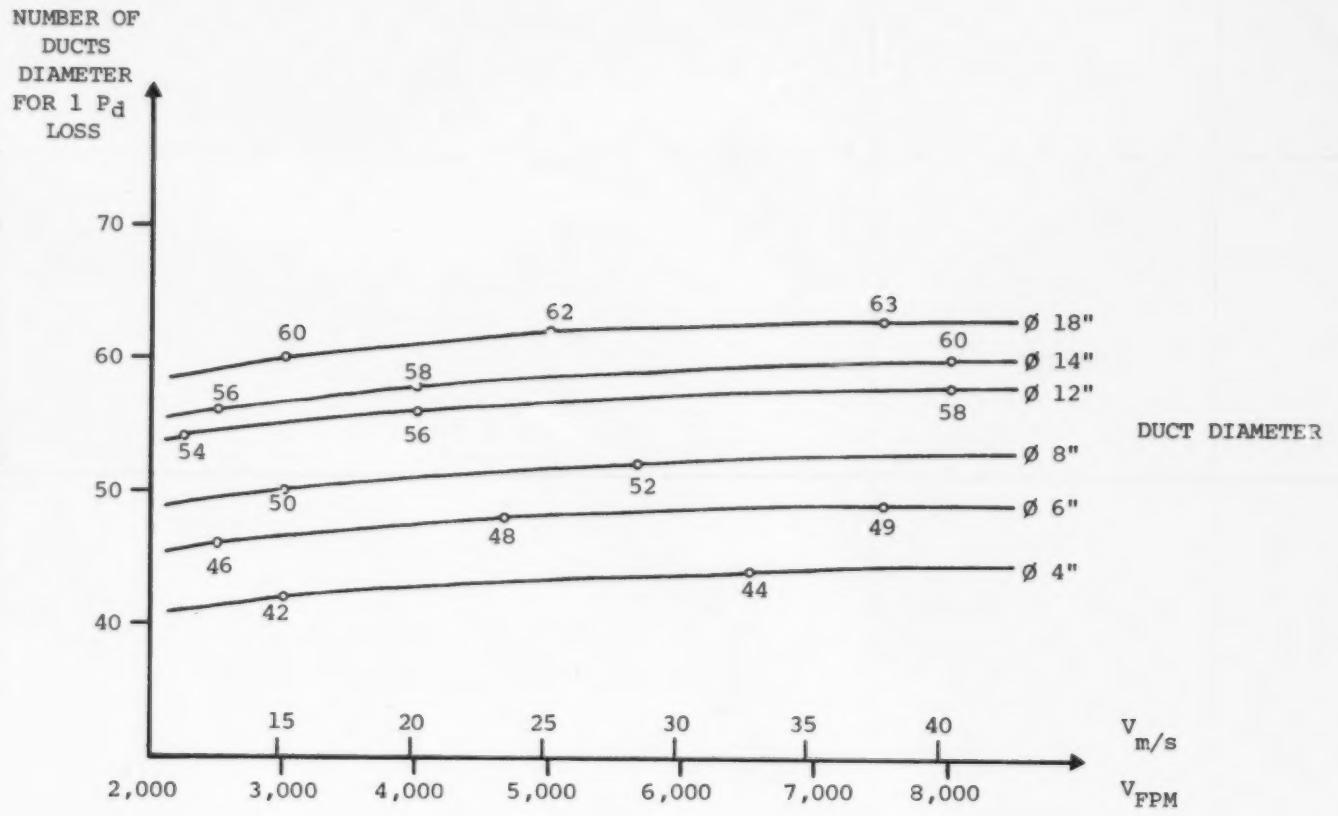


Figure 9. Number of duct diameters for one velocity pressure loss versus velocity.

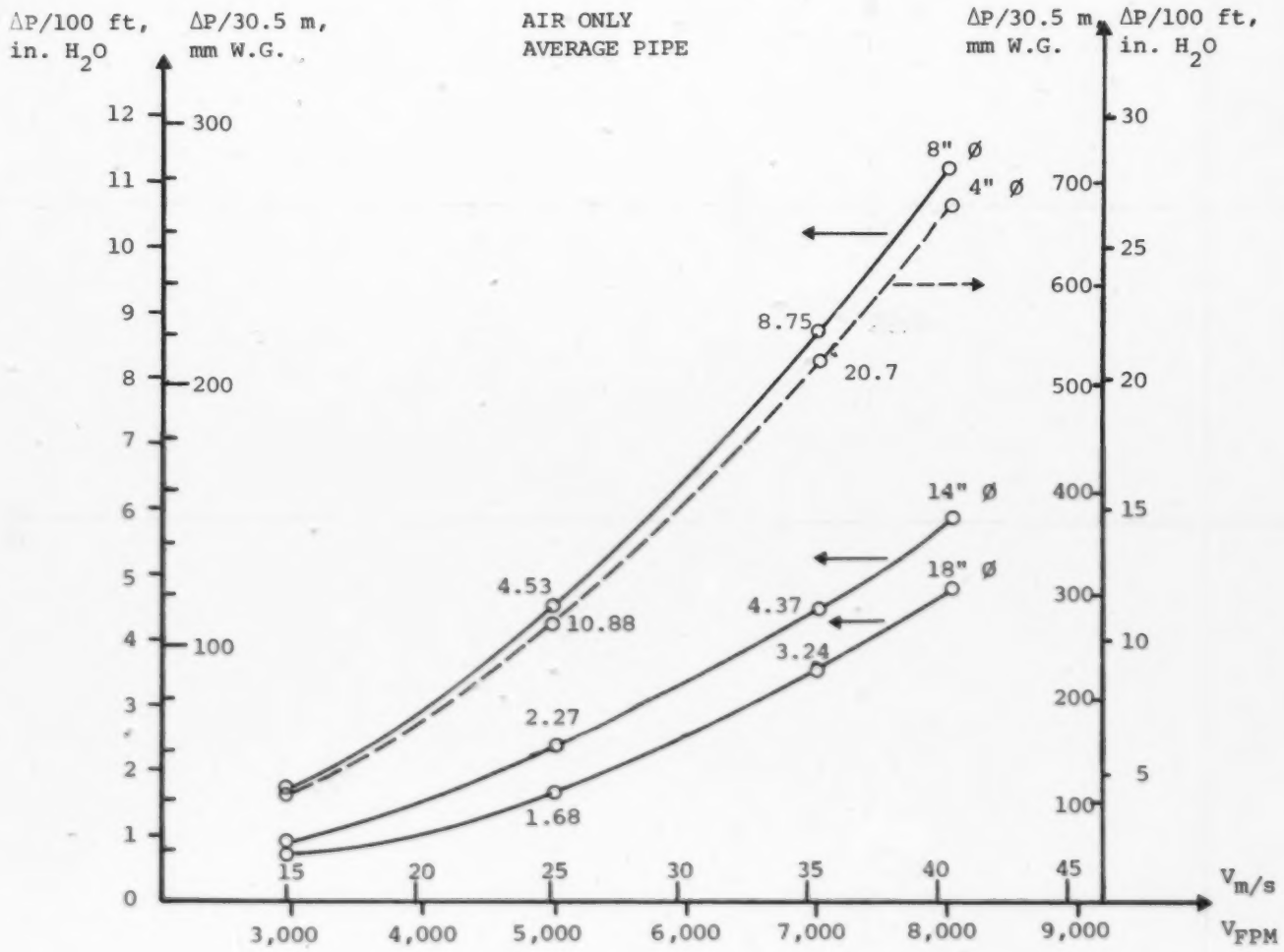


Figure 10. Pressure loss per unit length versus velocity (straight runs).

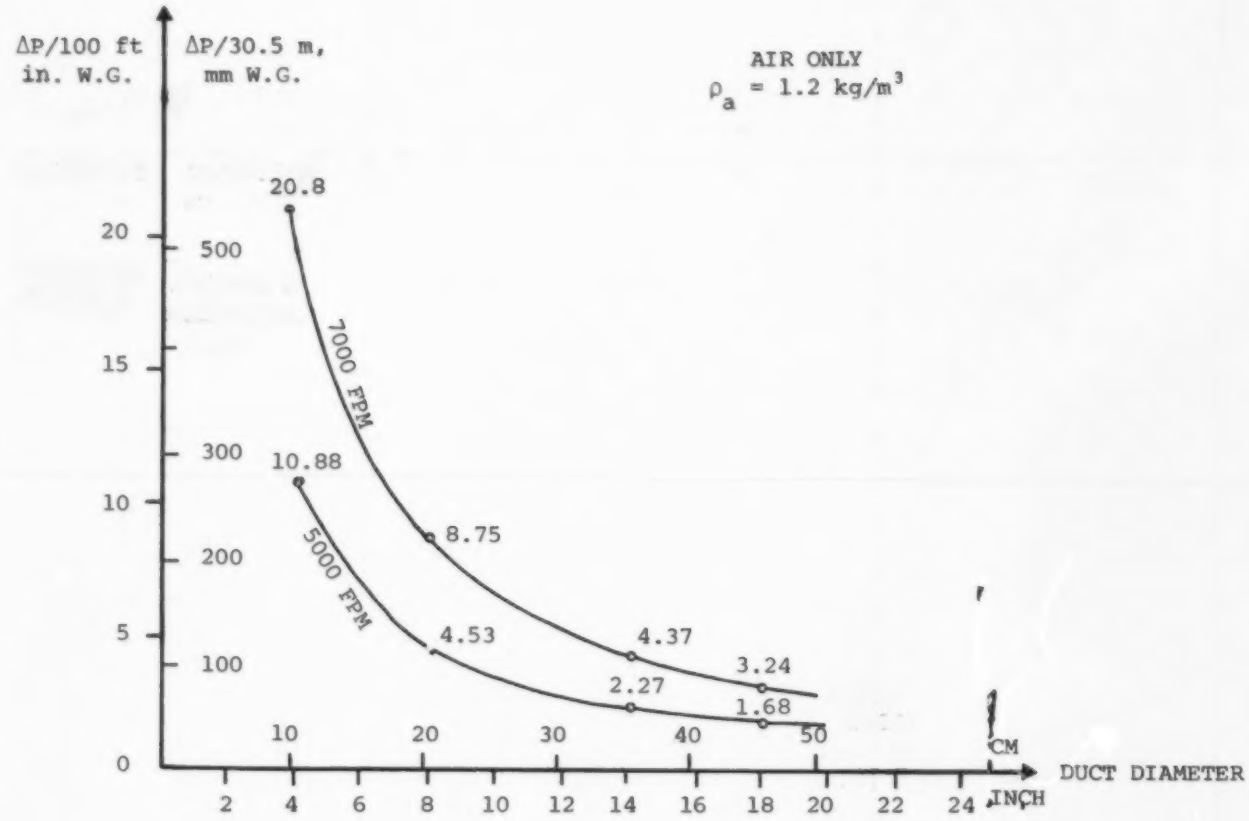


Figure 11. Pressure loss per unit length versus duct diameter.

(6000 FPM), this correction is a reduction factor of 0.85 or $\Delta P_{\text{straight runs}}$ = 212 mm W.G. (8.3 in. W.G.).

A3. Losses in elbows

The pressure loss in a smooth, well-contoured elbow is a function of the ratio of the radius of curvature, R_c, of the centerline to the diameter (height) of the duct, D_D (assuming turbulent flow). According to the Crane Co. (36), the resistance coefficient K (expressed as a fraction of the velocity pressure) has a minimum equal to approximately 12 f_t for R_c = 2 to 3, increases to 24 f_t for $\frac{R_c}{D_D}$ = 8 and 50 f_t for $\frac{R_c}{D_D}$ = 20. f_t is the fully developed friction factor for clean steel pipe. It is a function of the duct diameter D_D, equal to 0.017 for D_D = 0.10 m (4 in.); 0.014 for D_D = 0.20 m (8 in.); 0.014 for D_D = 0.25 m (10 in.); 0.012 for D_D = 0.46 m (18 in.) (34).

For an "ideal" elbow (R_c/D_D = 2 to 3), the loss in velocity pressure due to the elbow would be on the order of 20%, as shown on curve (A) in Figure 12. However, to avoid plugging and reduce abrasion, it is described as standard practice in pneumatic conveying to have, on the solids conveying side, elbows of minimum radius 4 ft. This means that R_c/D_D = 12 if the duct diameter D_D = 0.10 m (4 in.). As shown in Figure 11, it would lead to elbow losses significantly higher than 20% of the dynamic pressure. Figure 11 shows that for a duct diameter of 0.10 m (4 in.), the ΔP lost is 0.58 P_d, or by reference to Figure 6, at 30.5 m/s (6000 FPM),

$$\Delta P_{\text{elbows}} = 0.58 \times 57$$

$$= 33 \text{ mm W.G. (1.3 in. W.G.)}$$

A total of six elbows, as represented in Figure 12, would result in a loss on the order of 200 mm W.G. (7.8 in. W.G.), which is quite significant.

If, however, the elbows have a radius of curvature of 1.22 m (4 ft) for a duct diameter of 0.25 m (10 in.), then R_c/D_D = 4.88, and the total loss due to the six elbows is estimated to be (K = 15 f_t = 0.21), ΔP_{elbow} = 6 x 0.21 x P_d = 72 mm W.G. (2.8 in. W.G.).

A4. Losses in Y branches, pickup manifolds, diverted valves

According to Gerchow (18), for losses in Y branches, pickup manifolds or diverter valves, a pressure loss to 0.2 times the velocity pressure P_d should be allowed. For each such

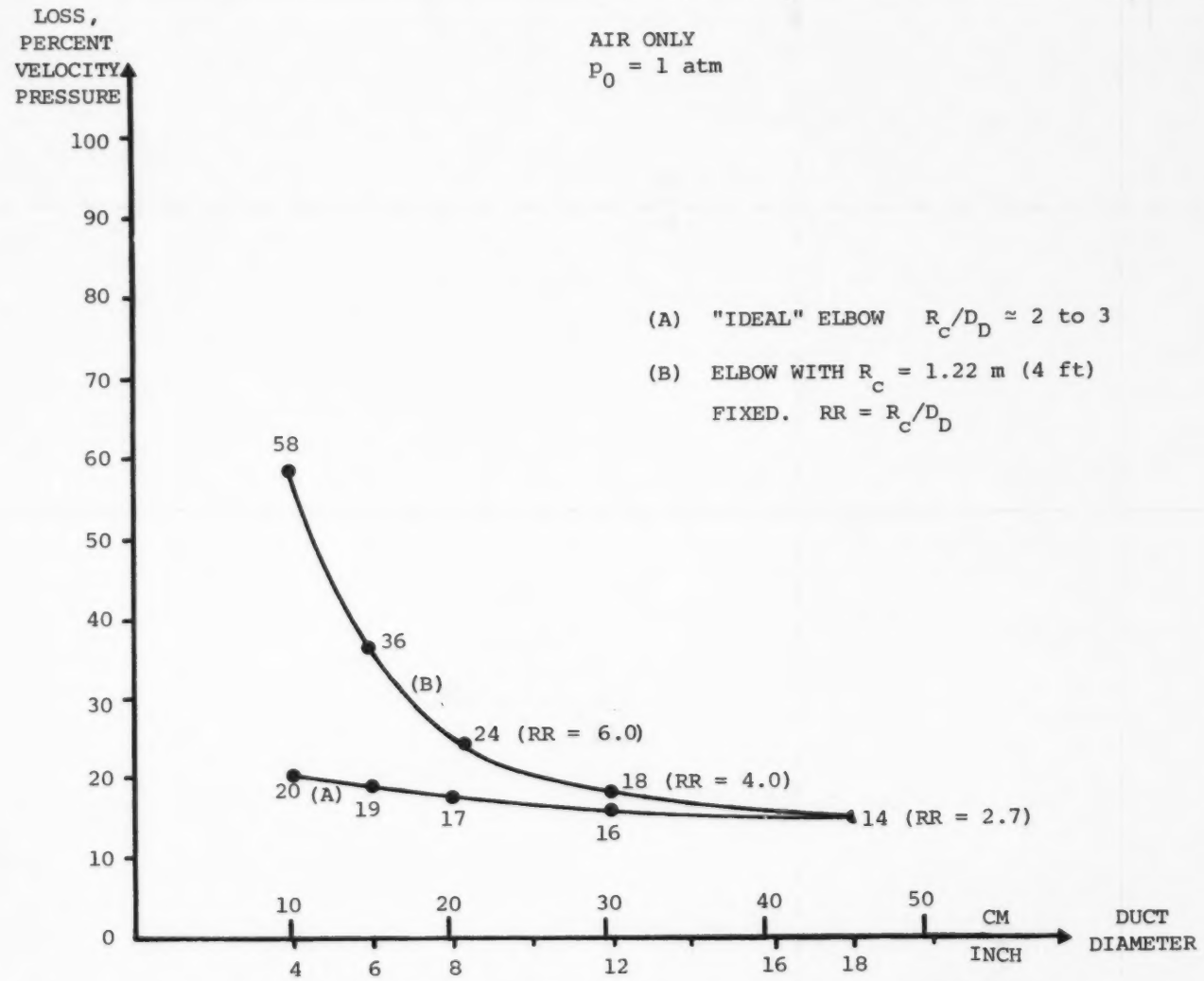


Figure 12. Pressure loss in elbows versus duct diameter.

elements, this amounts at ambient pressure and air density to a pressure loss of 11.4 mm W.G. (0.45 in. W.G.), at a conveying velocity of 30.5 m/s (6000 FPM).

A5. Losses in solids separator and filter

Cyclone collectors of high efficiency have a pressure loss estimated to be equal to two velocity heads (2 P_d) (18). For intermittent duty, a cyclone of medium efficiency, having a pressure drop of 1.5 P_d (32) would suffice. At 30.5 m/s (6000 FPM), this represents a pressure loss of $\Delta P_{cyclone}$ = 85 mm W.G. (3.4 in. W.G.).

An average pressure loss for the dust filters is estimated at about 75 mm W.G. (3 in. W.G.) (14), ΔP_{filter} = 75 mm W.G. (3.0 in. W.G.).

A6. Total pressure drop (air only)

Summing up the contributions from A1 through A5 (assuming no losses due to Y branches), gives the total ΔP: $\Delta P_{air\ only}$ = 477 mm W.G. (18.8 in. W.G.).

B. Losses Due to Solids --

Following the method outlined by Fisher (17) and Gerchow (18), additional pressure losses will result from accelerating, elevating and conveying the materials in the circuit.

B1. Acceleration losses

At the solids flow rate, $\dot{m}_s$ (kg/s) or SR x $\dot{m}_a$, the net mechanical power required to accelerate the solids from 0 to V_g (slip is neglected, conservatively) is, for an air volume flow rate $\dot{Q}_g$, $\dot{m}_s \cdot 0.5\ V_g^2 = \dot{Q}_g\ \Delta P_{s,acc}$. In this expression, $\Delta P_{s,acc}$ is the pressure drop caused by the acceleration of the solids. Substituting $\dot{m}_g/\rho_g$ for $\dot{Q}_g$, and SR = $\dot{m}_s/\dot{m}_g$, yields $\Delta P_{s,acc}$ = SR $\cdot$ 0.5 $\rho_g\ V_g^2$ = SR $\cdot$ P_d. At a maximum SR of 3, this term would be equal to three velocity heads or, for V_g = 30.5 m/s (6000 CFM), $\Delta P_{s,acc}$ = 171 mm W.G. (6.7 in. W.G.).

B2. Losses in vertical risers

The work per unit time corresponding to the elevation of solids mass $\dot{m}_s$ over a height Δh is, with $\Delta P_{s,v}$ the corresponding pressure drop, $\dot{m}_s \cdot \Delta h\ g = \dot{Q}_g\ \Delta P_{s,v}$ or $\Delta P_{s,v}$ = SR $\cdot$ ρ_g g Δh. For Δh = 11 m (36 ft), $\Delta P_{s,v}$ = 40 mm (1.6 in. W.G.).

B3. Losses due to friction against the wall

The coefficient of friction f_w (or tangent of the angle of slide) on a steel wall has been measured for various waste

fractions. Values are given in Part I of this contract (12).

In a worst case assumption, where it is assumed that all conveying is done in the circuit in contact with the wall of a horizontal duct (length ℓ_h), the pressure loss $\Delta P_{s,hor.}$ would then be: $g \dot{m}_s \cdot f_w \ell_h = P_{s,h}$, or $\Delta P_{s,h} = SR \cdot f_w g \ell_h \cdot \rho_g$. If $f_w = 0.6$ (paper on steel), $\ell_h = 61$ m (200 ft), $\rho_g = 1.2$ kg/m^3, $\Delta P_{s,h} = 36.6$ SR mm W.G. At the maximum solids-to-air ratio, SR = 3; $\Delta P_{s,h} = 131$ mm W.G. (5.2 in. W.G.). For one 90° elbow, if $V_s = V_g$ (conservative), the pressure loss due to the solids is $\Delta P_{s,e} = \pi f_w SR P_d$, or for $f_w = 0.6$, $\Delta P_{s,e} = 1.885$ SR P_d. For $P_d = 569$ mm W.G. (2.24 in. W.G.), corresponding to $V_g = 30.5$ m/s (6000 FPM), SR = 3, $\Delta P_{s,e} = 322$ mm W.G. (12.7 in. W.G.). However, for SR = 0.5 (recommended value for paper trim), $\Delta P_{s,e} = 54$ mm W.G. (2.1 in. W.G.). From this example, it can be seen that to keep the total pressure drop moderate (under 762 mm W.G. or 30 in. W.G.) will be necessary to use no more than one elbow in the circuit at SR = 3, two at SR = 1 and/or to reduce the total length of straight runs from 61 m (200 ft) to 30.5 m (100 ft) or 15.3 m (50 ft).

B4. Total losses due to solids

These losses will be obtained by summing up contributions B1, B2, B3.

For the maximum solids-to-air ratio, SR = 3, the pressure drop due to the solids would be at $V_g = 30.5$ m/s (6000 FPM); $\Delta P_s = \Delta P_{s,acc} + \Delta P_{s,v}^* + \Delta P_{s,h} + \Delta P_{s,e\ell}$. For six 90° elbows in series, $\Delta P_s = 171 + 131 + 6 \times 322 = 2234$ mm (88.0 in. W.G.). Keeping only one elbow and two straight sections (horizontal) at SR = 3 would reduce this pressure significantly, $P_s = 171 + 66 + 322 = 559$ mm (22 in. W.G.). For the same configuration, at SR = 1, $P_s = 57 + 22 + 107 = 186$ mm (7.3 in. W.G.).

Total Pressure Losses and Required Horsepower --

From the above analysis, it is possible to define a variety of options resulting in systems of different complexity and costs.

At one end of the spectrum, the maximum system, comprising the full four straight runs of 15.3 m (50 ft) each, and six 90° elbows, would require, to operate at solids-to-air ratios SR up to 3, $\Delta P_{TOTAL} = 477 + 2234 + 2711$ mm W.G. (106.7 in. W.G.). For a static efficiency of 65%, the fan power required would be:

$$HP_{FAN} = \frac{1.55 \times 2771 \times 9.81}{.65} = 63{,}418 \text{ watts} = 85 \text{ HP}$$

*Optional; $\Delta P_{s,h}$ correspondingly reduced.

Providing for transmission efficiency and a power margin, this would necessitate a 100 HP drive assembly.

At the other end of the spectrum, a minimum system could be defined, which might sufficiently meet the overall purpose if not the letter of the specification. Namely, at high air velocity or solids-to-air ratio, only one 90° elbow is investigated, and the length of straight runs is shortened appreciably, for example, to one 7.6 m (25 ft) section immediately upstream of the elbow, and another one, of length, immediately downstream of the elbow.

Under these assumptions, for SR = 3,

ΔP_{air} = 71 + 62 + 12 + 85 + 75 = 305 mm W.G. (12 in. W.G.)

ΔP_{solids} = 171 + 33 + 322 = 526 mm W.G. (20.7 in. W.G.)

ΔP_{TOTAL} = 831 mm W.G. (32.7 in. W.G.).

Relaxing the specification to SR_{max} = 2, ΔP_{TOTAL} = 305 + 114 + 22 + 215 = 656 mm W.G. (25.8 in. W.G.). A fan with a ΔP of 656 mm W.G. (25.8 in. W.G.) would suffice, delivering approximately 1.55 m /s (3270 CFM), and requiring 19,950 W (26.7 HP) for a static efficiency of 50% (radial blades, backplate, flow-through materials fan).

Layout and Specifications of Pneumatic Test Rig

In view of the objectives of the test rig already listed below, a proposed layout of a test rig was established and attached to the Specification Document sent to vendor for quotes on list, size and cost of equipment (see following sub-section).

Conceptually, as sketched in Figure 13, the test circuit would consist of a succession of

- straight runs, of such length (compared to the diameter) that the flow should become fully established at mid-length. For a duct diameter of 0.25 m (10 in.), this would mean a total length of straight run of no less than about 10 m (33 ft)

- elbows, of soft bend ($R_{curvature}$ = 1.25 to 2.0 m (4 to 7 ft)), for D_D = 0.25 m (10 in.))

- vertical risers of length on the order of 15 to 20 diameters, or 3 to 5 m (12 to 17 ft) for D_D = 0.25 m (10 in.)

- a solids feeding device (scoop, gravity-fed hopper, rotary air lock, etc.)

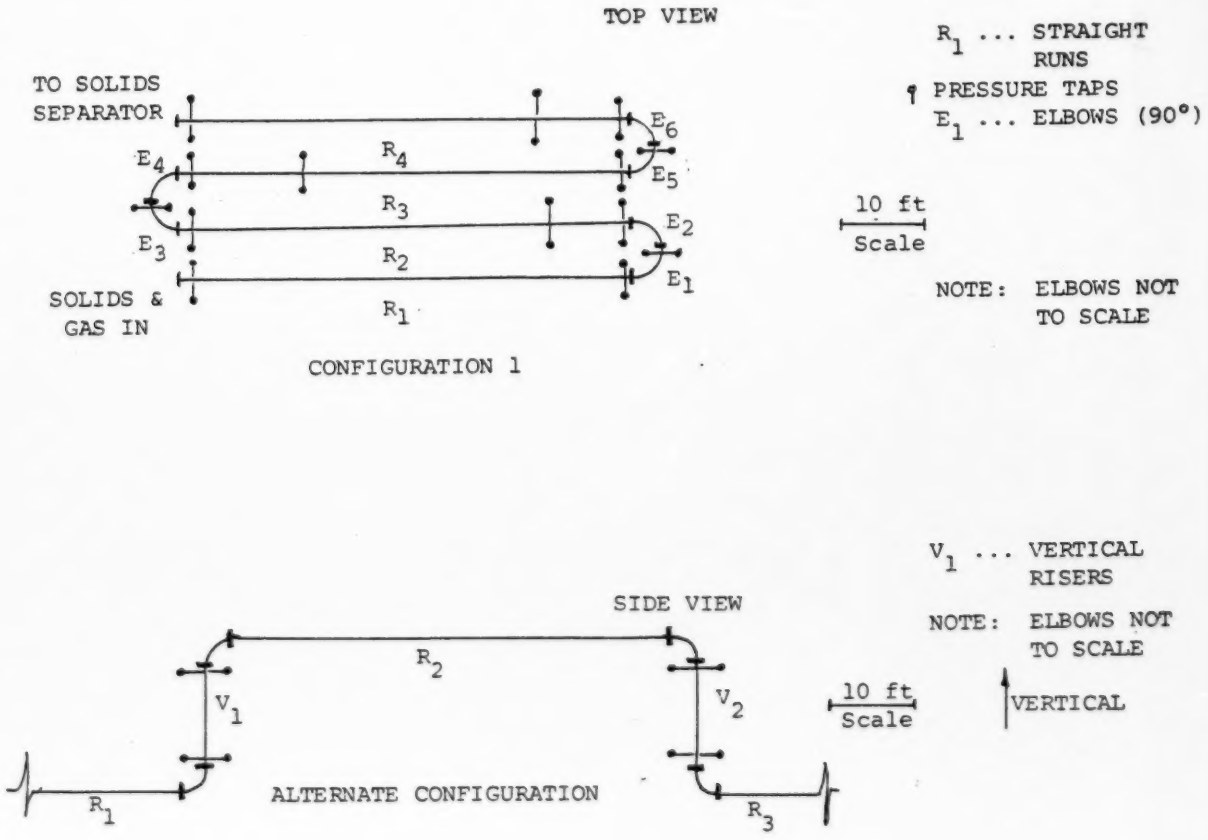


Figure 13. Pneumatic test rig. Passive circuit. Schematic view.

- a solids separator (cyclone or equivalent)

- a fine dust filter system.

A rapid calculation, using the approximate developments of the two preceding sub-sections, shows that within reasonable pressure limits (D_p = 635 to 762 mm W.G.) (25 to 30 in. W.G.) up to 61 m (200 ft) of circuit, at least one elbow, a cyclone and a dust filter (bag-type) can be accommodated, provided only the two lighter fractions (RDF, shredded MSW) are being conveyed. It thus appears reasonable to specify the total length of the straight runs in the loop at approximately 61 m (200 ft).

Pressure taps will be placed at each measurement point to determine the static pressure, at zero or non-zero solids loading. Typically, these would be located at

- the blower inlet and outlet

- the beginning and end section of each straight run, vertical riser, and elbow

- the inlet and outlet of the cyclone and filter.

These considerations were used in the definition of the specifications, and the system geometry given in the following section and Figure 13 respectively.

PNEUMATIC CONVEYOR
TEST RIG SPECIFICATIONS

Purpose: The purpose of the test rig is to experimentally study the pneumatic conveying characteristics of selected fraction of processed municipal solid waste (MSW). More specifically, it is intended to determine:

- Under which conditions of gas velocity, pressure, solids-to-gas ratio, mass flow rates (air or solids), trouble-free, clog-free, reliable steady operation is maintained.

- Investigate the effect of feedstock moisture on the above.

- Quantitatively, to determine the increase in circuit resistance (as measured by the static pressure drop per unit length of circuit, $\Delta P/L$) resulting from the presence of the solids conveyed, as compared to the circuit resistance with air only. Symbolically, for a given material:

  $$\Delta P/L = F \text{ (Velocity of gas, solids ratio)}$$

  This will be done for elements such as straight runs of duct, vertical risers, 90° elbows.

- Also, to determine the variations of the fan or blower operating point (ΔP, CFM; power or efficiency, CFM) on its characteristic curves, possibly at different fan operating speeds.

Materials: A tentative list of four (4) materials, their properties and particle size distribution is listed in Table 6. It is not expected that all materials could be handled by the set-up proposed. In order of priority, the test rig should be able to accommodate: material (1) (RDF); then material (2) (shredded MSW). If feasible with the same set-up as for (1) and (2), the pneumatic conveyability of material (4) ferrous fraction, the material (3) (heavy fraction) should be considered.

TABLE 6. PROPERTIES OF MATERIALS TO BE CONVEYED*

	RDF (1)	Shredded MSW (2)	HF (3)	Ferrous Fraction (4)
Moisture % as rec'd	15-20	29.7	20.00	2.6
Bulk Density lb/ft	2.33	7.83	20.92	12.1
Angle Slide, °	31	29.3	27.5	18.0
Description	Paper, plastics, light fabrics.	Paper, light metals, glass, plastics.	Cans, (Fe,Al), cardboard, textiles, rubber, wood.	Steel cans, pieces of steel.
PSD% (wt)				
+ 4"	-	4.1	1.2	28 (< 6")
+ 3"	-	7.1	0.8	26
+ 2"	0.6	12.15	12.5	36
+ 1"	4.8	12.25	23.4	9
+ 1/2"	57.8	15.7	18.0	0
+ 1/4"	21.3	17.6	20.2	1
+ 6 mesh	5.4	12.3	14.1	0
- 6 mesh	10.1	18.8	9.3	

* As sent to vendors.

Type of System: The system can be positive pressure, vacuum or balanced vacuum-pressure. If possible, passage of the materials through the fan should be avoided (however, this is not a stringent constraint).

Gas Velocities: Although the conveying velocities would have to measured experimentally, they are expected to be in the neighborhood of 28 to 33 m/s (5500 - 6300 fpm).

Solids Ratio: The range to be spanned is expected to be 0.05 to 3 lb solids/lb air.

Continuous Operations: For all solids ratio, continuous operation should be maintained for no less than 1 minute, in the most unfavorable case and preferably several minutes to permit data acquisition. It is foreseen that limitations in mass or volume of feedstock sample weight and volume are about 1 Mg, 10 m^3* (whichever applies first), batch fed to simulate continuous operation.

Mode of Feeding: Should be appropriate for the type of system selected. For example, feeding through rotary air lock or air scoop, if steady and technically feasible, would be acceptable. Metering system should be capable of maintaining steady flow of ± 10%.

Equipment Duty: The proposed test rig is assumed to be located under roof on a level site. Weather conditions and altitude are typical of Washington, D.C. As this is a test rig with limited life, high durability in piping components is not necessary.

Equipment and Circuit: The proposed test rig shall include:

- Solids feeding device (1 pick up or inlet)
- Solids separator, with filter to capture all of sample (to permit multiple use of sample) and/or control dust.
- Fan, or blower or compressor, with electric drive, on base; air volume control and associated belts, pulleys controls and other hardware.
- A circuit for solids conveying consisting of (Figure 13)

*Compute on the basis of bulk density = 80 kg/m^3 (5 lb/ft^3).

- 200 ft of straight runs with support structures.

- 6 smooth elbows ($R_C/D_D \approx 5$ to 8) @ 90°.

- 2 Lexan (or equivalent) 2 dimensional 90° elbows, for slow visualization studies, with replaceable walls.

- 1 Lexan (or equivalent) circular cross-section element of ducting, 6-foot-long, for visualization studies, with replacement walls.

- 2 transformation pieces (circular to square) from duct to plastic elbow; elbow to duct.

- 2 vertical (1 ascending, 1 descending) risers 12 ft long each, delivered separately, which could be connected to straight runs in another series of experiments (Figure 13) with support structures.

Each of the straight runs shall be equipped with two pressure taps, at each end, one on the inner and one on the outer walls (with respect to the elbows); additional taps as indicated. Quote: FOB Plant. Shall include shipping wt and CFT. The quote should specify component sizes, fan characteristics and auxiliary motor sizes; provide envelope layout with overall area and height requirements; indicate foundation requirements and proposed assembly techniques.

Experimental Plan

A. Materials --

A1. Materials sampled and tested will be: (a) RDF; (b) shredded MSW, and if they can be accommodated by the test rig; (c) ferrous fraction; and (d) examples of particle size distributions are given in Table 6.

A2. Materials will be characterized by: loose and compacted bulk density; moisture content; composition by component and screen size; PSD (conventional); PSD (non-conventional: aspect ratio of in-plane dimensions; height to in-plane size ratio; surface-to-mass ratio); ballistic properties (as indicated).

The list will be culled or possibly extended as advised based on the results of previous tests.

A3. Materials will be checked, if required, for assessment of moisture changes or particle size reduction during any previous pneumatic conveying loop through the system. (This is necessary, for example, if the materials flow through the conveying fan. The moisture checks verify the feed consistency if the material is used for several tests.)

A4. Quantity. For a known air flow rate, the target solids flow rate will be fixed for each experimental point, and varied over the range needed to explore the range of solids to air ratio, SR, $0 \leq SR \leq 3$.

As shown above, the amount to be tested will be on the order of, but in no cases greater than, 1000 kg (2200 lb), and furthermore, the volume of materials should not exceed 10 m^3 (352 ft^3).

B. Air Flow --

B1. Setting. The air flow under solids load will be fixed based on the estimated required conveying velocity. The fan speed will be adjusted to reach the target solids-to-air ratio. In predicting an approximate operating point under load, computed figures for the pressure drop over the total circuit will be obtained using the procedures outlined above.

B2. Measurement. Determination of the air flow rate (capacity) in the circuit will be carried out by pitot or anenometric techniques (under load), but in a section located before injection or after removal of the solids; or using fan characteristics curves (under no load) and pressure measurements (ΔP) through the blower (under load). The power absorbed by the fan will also be determined by reading the power consumption of the electric drive.

C. Pressure Measurements along the Circuit --

C1. As shown in Figure 13, static pressure measurements will be carried out, both under no load and under load, at the inlet and outlet section of circuit elements: fans, straight runs, vertical risers, elbows, cyclones and filters.

For a fixed material, and a fixed element, curves will be drawn giving, per unit length L, the static pressure drop $\Delta P/L = F(V_a, \dot{m}_s)$. It is estimated that no less than four different velocities and six solids flow rates (SR = 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0) would be required for each material tested.

D. Minimum Velocity --

D1. Starting with an air velocity well above the minimum safe velocity, the air velocity and solids mass flow rate will be decreased by steps, simultaneously, so as to maintain a constand solids-to-air ratio. The incipient velocity (or possibly velocity range) where saltation, plug or a no-conveying situation are noted, visually or by recording local increases in pressure across elements, will be characterized by a value V_{min}.

V_{min} will be recorded as a function of the solids-to-air ratio for a given material.

E. Qualitative Observations --

E1. Qualitative observations on ease of feeding, adherence, tackiness, effect of moisture, abrasivity (if observable), plugs, saltation will be made during and after each test, and duly recorded.

F. Visualization of Solids Conveying --

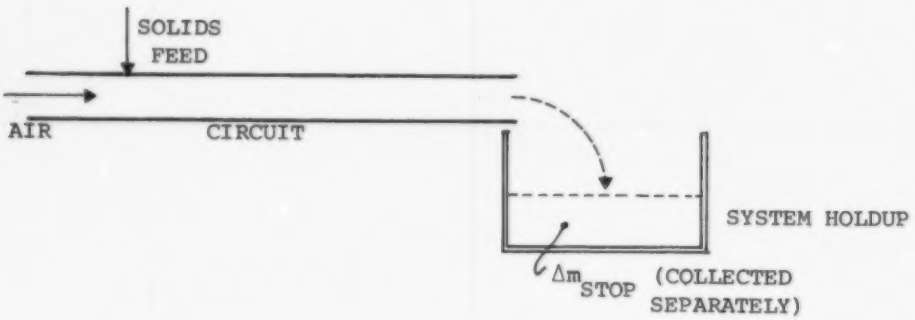
F1. Visualization of solids flow (particle attitude, velocity slip, coalescence, etc.) will be made in a transparent section of a straight run, a vertical riser and a 90° elbow, using high-speed cameras and videorecording equipments, and high speed photography. Experimental observations of the velocity slip will be compared to those derived from the determination of the system solids hold-up and transit time, upon sudden stoppage of the feed, i.e., (Figure 14) $m = \Delta m_{stop}/\Delta t_{stop}$, in which Δm_{stop} is the mass present in the system at $t = 0$ when solids feeding stops, and collected over time interval $(0, \Delta t_{stop})$.

Manufacturers' Quotes

Over the course of the investigation, detailed technical consultations, by letter, on the phone and during plant visits, were held with waste pneumatic conveying equipment manufacturers. A list of such manufacturers, which is reasonably complete but does not claim to be exhaustive, is given in Appendix C. No endorsement is implied. Manufacturing and laboratory installations visited by this author are also listed in this appendix.

On the basis of these contacts and visits, quotes were requested from three experienced firms having expressed an interest in sizing and costing the pneumatic conveyor test rig described in the above specification.

As stressed above, it is possible, if the specification on the range of solids-to-air ratio ($0 \leq SR \leq 3$) is somewhat relaxed ($SR_{max} = 2$) and the loop length and number of elbows is reduced at high solids loadings, to define a relatively



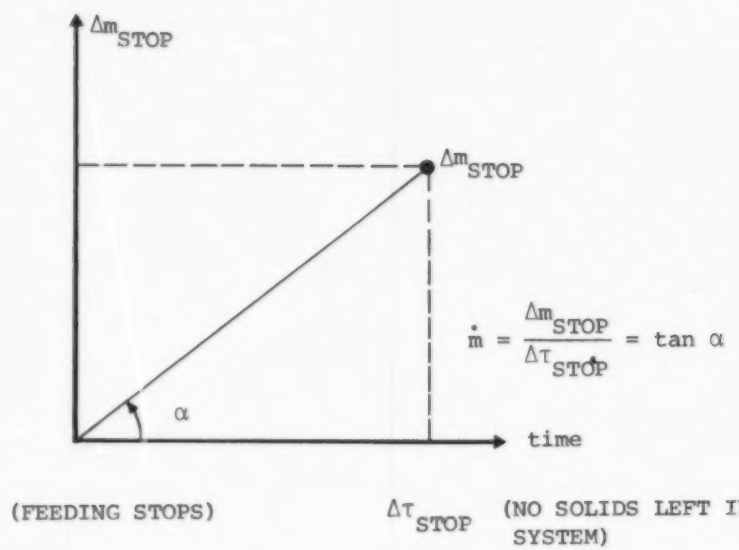


Figure 14. Schematic of solids flow rate and circuit holdup determination by feed stoppage.

inexpensive, simple system. It will accommodate materials (1) RDF, and (2) shredded MSW in Table 3, and possibly light can-stock. (Minimum system) On the other hand, a solution strictly meeting the specification, and aimed at conveying all four materials, is a relatively high-vacuum system, having much higher requirements in pressure (2500 mm W.G. and up) and power (about 100 HP). Table 7 summarizes the results of the request for quotes.

Although the price range is quite considerable, it spans the whole array of options available. The costlier system allows a complete investigation over the range of solids-to-air ratios, with a fixed geometry of the passive circuit. The less costly alternative requires that the loop tested be shortened or lengthened depending on the solids loadings, and at most one elbow could be studied at one time at the high solids ratios.

Besides the straight purchase option, an alternative explored with the manufacturers was that of testing materials at their site, using their existing test rigs and equipment (see cover letter, Appendix A2). In this case, the length of the circuit would in most cases fall somewhat short of 61 m (200 ft), and less flexibility would exist in the definition of the geometry of the test loop (elbows, risers, etc.) or horsepower requirements (existing fans, motors, etc.). Manufacturers' per day of testing (including technical personnel required) were in the range:

Cost per day of testing:	$750 to $1,000	
Number of days required:	Set up pressure taps:	3
	8 materials* @1 material/day:	8
	Disassembly and cleanup:	1
	Total	12
Total cost of test series:	$12,000/series (at $1,000/day)	

From the above, it is apparent that investment in either the simplified or more complete system would be justified only if a number of test series were contemplated. For example, if the cost of test series (personnel and overhead) were $500/day at our site, the number of test series required (over a period of 1 year, say) required for payback would be:

*By convention, defines a "test series."

TABLE 7. SUMMARY OF MANUFACTURER'S QUOTES

Option	Equipment & List Description	Comments	Price Range
1) Minimum System S1 (14" diameter duct)	200 ft of galvanized metal pipe (14" dia.), elbows, fittings cyclone separator (6'6") and support frame heavy duty material handling fan 20" W.G. S.P. 40 HP drive fan motor assembly base set of V belt drives; dust filter	Fan immediately upstream of cyclone (negative - positive pressure system)	$30,000 (allowance made for freight, taxes and assembly at our site)
2) Minimum System S2 (10" diameter duct)	200 ft of galvanized metal pipe (10" dia.), elbows, fittings cyclone separator (5'2" dia.) and support frame heavy duty material handling fan, 24" W.G. 30 HP drive fan and motor assembly base set of V belt drives dust filter	IDEM.	$25,000 (allowance made for freight, taxes and assembly at our site)

Table 7. (cont'd)

Option	Equipment & List Description	Comments	Price Range
3) Maximum System S3 (10" diameter duct)	open inlet hopper (10 m^3 capacity) 2 HP vibrating bin discharge vacuum type manifold, 61 m (200 ft) of 10" schedule pipe, eight 90° elbows, couplings positive displacement blower, 117" W.G. S.P., 2760 CFM, 100 HP drive gravity flow hopper 1.8 m diameter x 7.3 m height motor drive, TEFC, 100 HP air filter, 50.2 m^2 (540 sq. ft.), 432 mm (17 in.) Hg design	vacuum (all negative pressure) conveying system positive displacement blower (vacuum) downstream of air filter	$155,000 (allowance made for freight and taxes and assembly at our site)

Minimum system: $n = \frac{30,000}{12,000 \times 0.5} \simeq 5$ series

Maximum system: $n = \frac{155,000}{12,000 \times 0.5} \simeq 26$ series

These figures should be assessed in the particular market situation. In the case of a non-profit research facility deriving the bulk of its support from governmental contracts and grants, it is this author's view that realistic market expectations might permit the purchase of a minimum system, as defined. Experiments of the type, and over the ranges of loadings, allowed by the maximum system would be in all likelihood more advantageously carried out at the manufacturer's test laboratory, and paying for the use of such facility and expert services.

SUMMARY AND CONCLUSIONS

A short study and analysis of the characteristics, expected capabilities, and design requirements have been conducted for a pneumatic conveying test rig handling shredded MSW and its processed fractions. Typical requirements on conveying speed, solids loading, duct sizing, air mover pressure and horsepower requirements were examined. From existing references, suggested calculation guidelines were outlined.

Based on specifications evolved from the analysis, quotes were obtained from manufacturers for a pneumatic test rig capable of handling 1 Mg or 10 m^3 of waste in a batch mode. A fixed geometry system of high resistance would be justified only if it were foreseen that a large number of tests would be run quite regularly over a period of years. Otherwise, tests performed at the manufacturers' sites make more economic sense. On the other hand, a simplified, variable geometry (length, number of elbows) system of restricted capabilities could be consdiered for purchase, even with the assumption that the test rig would be used only for a few months over the year.

REFERENCES

1. Descamps, P., and C. Jodlowski. Théorie et Expérience en Manutention Pneumatique. (Theory and Experiments in Pneumatic Conveying. In French.) Le Courrier des Etablissements Neu, Revue Technique, #56, Lille, France, July 1972. pp. 3-14.

2. Courtney, W. Pneumatic Transport of Refuse-derived Fuel (over 600 m and over 15 kg/s). Pneumotransport 5. In: Proceedings of the Fifth International Conference on the Pneumatic Transport of Solids in Pipes, London, U.K., April 16-18, 1980. pp. 389-402.

3. Murphy, J. D. Materials to Resist the Abrasion of Pneumatically Transported Processed Refuse. Energy Conservation Through Waste Utilization. In: Proceedings of the 1978 National Waste Processing Conference, ASME, Chicago, Illinois, May 7-10, 1978. pp. 327-340.

4. Scaramelli, A. B., R. T. Felago, S. J. Fischer, R. W. Pease, J. B. Quinn, and P. J. Stoller. Resource Recovery Research, Development and Demonstration Plan. Technical Report MTR-79W00173, Contract EM-78-C-01-4241, U.S. Department of Energy, Mitre Corp., Bedford, Massachusetts, 1979. p. 71.

5. Op. cit. Ref. (2). p. 391.

6. Op. cit. Ref. (1). p. 7.

7. Renard, M. L. An Analysis of Removal of Ash Components from Refuse-derived Fuel during Pneumatic Transport. Final Report, Contract ES-76-C-01-3851/7, Urban Waste Technology Branch, U.S. Department of Energy, National Center for Resource Recovery, Inc., Washington, D.C., August 1979.

8. Op. cit. Ref. (1). p. 8.

9. Cyffers, M. Le Comportement des Rotors de Ventilateurs Véhiculant des Fluides Très Chargés en Poussières. (Behavior of Fan Rotors Carrying Extremely Dusty Gas Flows. In French.) Paper presented at 1973 Colloquium on Abrasion, Industrie Minérale, Paris, France. pp. 1-12.

10. Op. cit. Ref. (1). p. 12.

11. Renard, M. L., and Z. Khan. Design Considerations for Municipal Solid Waste Conveyors. Municipal Solid Waste: Resource Recovery. In: Proceedings of the Seventh Annual Research Symposium, U.S. Environmental Protection Agency, Philadelphia, Pennsylvania, March 1981. pp. 30-66.

12. Khan, Z., M. L. Renard, and J. Campbell. Considerations in Selecting Conveyors for Solid Waste Applications. Final Report, Part I, Grant R80679091, U.S. Environmental Protection Agency, Cincinnati, Ohio, National Center for Resource Recovery, Inc., Washington, D.C., July 1981.

13. Winkler, D. F., and D. G. Wilson. Size Characteristics of Municipal Solid Waste. Compost Science, 14(5):6-11, 1973.

14. Ruf, J. A. Particle Size Spectrum and Compressibility of Raw and Shredded Municipal Solid Waste. Ph.D. Dissertation, University of Florida, Gainesville, Florida, 1974.

15. Trezek, G. J., L. F. Diaz, G. M. Savage, and R. White. Prediction of the Impact of Screening on Refuse-derived Fuel Quality. Report EPRI RP 1180-6, Cal Recovery Systems, Inc., Richmond, California, June 1979. pp. 2-1 - 2-3.

16. Zandi, I. Pipeline Transportation of Solid Wastes. In: Handbook of Solid Waste Management (D. G. Wilson, Ed.), Van Nostrand Reinhold Co., New York, New York, 1977. p. 117.

17. Fischer, J. Practical Pneumatic Conveyor Design. Chemical Engineering, June 2, 1958. pp. 114-118.

18. Gerchow, F. How to Select a Pneumatic Conveying System. Chemical Engineering, February 17, 1975. pp. 73-86.

19. Stoess, H. S., Jr. Pneumatic Conveying. Wiley Interscience, New York, New York, 1970.

20. Kraus, M. N. Pneumatic Conveying of Bulk Materials. Ronald Press Co., New York, New York, 1968.

21. Fan Engineering. (R. Jorgensen, Ed.) 7th Edition. Buffalo Forge Co. Publ., Buffalo, New York, 1970.

22. Descamps, P., and C. Principes et Bases due Transport Pneumatique et de la Fluidisation. (Principles and Bases of Pneumatic Conveying and Fluidization. In French.) Le Courrier des Etablissements Neu, Revue Technique, #56, Lille, France, July 1972. pp. 15-27.

23. Soo, S. L. Fluid Dynamics of Multiphase Systems. Blaisdell Publishing Co., Waltham, Massachusetts, 1967.

24. Tanzer, E. K. Pneumatic Conveying for Incineration of Paper Trim. In: Proceedings of the 1968 National Incineration Conference, ASME, New York, New York. pp. 309-317.

25. Op. cit. Ref. (21). pp. 486-487.

26. Gasterstadt, M. Experimental Investigation of Pneumatic Conveying Process. ZDVI, 68(24), June 14, 1924.

27. Renard, M. L. Technological Barriers to the Recovery of Secondary Fibers from Municipal Solid Waste. In: Proceedings of the 1978 Pulping/Secondary Fibers Conference of the Technical Association of the Pulp and Paper Industry (TAPPI), New Orleans, Louisiana, November 6-8, 1978. pp. 333-345.

28. Renard, M. L. Selective Dry Processing, Pulp Cleaning and Paper Making Tests on Three Feedstocks from Municipal Solid Wastes. In: Proceedings of the 1979 Pulping/Secondary Fibers Conference of the Technical Association of the Pulp and Paper Industry (TAPPI), Seattle, Washington, September 1979. pp. 247-258.

29. Op. cit. Ref. (18). p. 80.

30. Op. cit. Ref. (22). Fig. 15, p. 21.

31. Ibid. p. 20.

32. Neu Company, Lille, France. Private communication, 1979.

33. Madison, R. D., and W. R. Elliot. Friction Charts for Gases including Correction for Temperature, Viscosity and Pipe Roughness. ASHVE Journal Section of Heating, Piping and Air Conditioning, October 1946. pp. 107-112.

34. Op. cit. Ref. (21). p. 487.

35. Ibid. p. 102.

36. Crane Corp. Flow of Fluids through Valves, Fittings and Pipes. New York, New York. p. A-29.

37. Ibid. p. A-26.

APPENDIX A

PNEUMATIC CONVEYING OF MSW FRACTIONS: TYPICAL OPERATING PARAMETERS AT SAMPLE U.S. FACILITIES

The following data were gathered from the end of 1980 to mid-1981. They were gathered by NCRR engineers from the literature, during site visits, and from correspondence and telephone interviews. Every attempt was made to obtain accurate and up-to-date information, although the latter could not be independently verified. In view of the diversity of the "formats" in which data could be handled, plants are listed sequentially rather than as elements in a summary table.

1. Ames, IA

	Plant to Storage	Storage to Boiler
Pipe Dia.	0.356 m (14 in.) Quantity: one	0.203 m (8 in.) Quantity: four
Pipe Length	200 m (656 ft)	122 - 137 m (400 - 450 ft)
System Blower and Type	Positive displacement, air lock	Positive displacement, air lock
Product	38 mm (1.5 in.) RDF	38 mm (1.5 in.) RDF
Air Volumetric Flow Rate	3.0 m^3/s (6357 CFM)	1.1 m^3/s (2231 CFM), per pipe
Solids Mass Flow Rate	22.7 - 27.2 Mg/h (25 - 30 TPH)	3.6 - 8.2 Mg/h (4 - 9 TPH)
Fan Drive HP	149 kW (200 HP)	45 kW (60 HP) per pipe
Solids/Air Ratio, SR (kg solids/kg air)	1.93 @ 25 Mg/h, 3.0 m^3/s	1.24 @ 5.9 Mg/h, 1.1 m^3/s

2. Akron, OH	
	Metering Bin at Storage Site to Fuel Storage
Pipe Dia.	203 m (8 in.) Quantity: three lines
Pipe Length	69.6 m (300 ft)
System Blower and Type	Positive displacement blower, air lock
Product	76 to 101 mm (3 to 4 in.) RDF
Air Flow, Original System	1.51 m^3/s (3200 CFM)
Solids Flow, Original System	11.3 Mg/h (12.5 TPH)
Fan Drive HP, Original System	74.6 kW (100 HP)
Air Flow, Modified System	1.84 m^3/s (3900 CFM)
Solids Flow, Modified System	11.3 Mg/h (12.5 TPH)
Fan Drive HP, Modified System	112 kW (150 HP)
Solids-to-Air Ratio, Original System	1.73
Solids-to-Air Ratio, Modified System	1.42
3. Madison, WI	
	Storage to Boiler
Pipe Dia.	0.203 m (8 in.) Quantity: one
Pipe Length	Two sections, 45.7 m (150 ft) and 24.7 m (81 ft)
System Blower and Type	Positive displacement blower, air lock
Product	19 mm (3/4 in.) RDF
Air Flow	0.9 m^3/s (1895 CFM)

3. Madison, WI (cont'd.)	
	Storage to Boiler
Solids Flow	3.6 - 4.5 Mg/h (4 - 5 TPH), average 9.1 Mg/h (10 TPH), design
Fan Drive HP	30 kW (40 HP)
Solids-to-Air Ratio, SR, kg Solids/kg Air	1.16 @ 4.5 Mg/h, 0.9 m^3/s and 2.34 @ 9.1 Mg/h, 0.9 m^3/s
4. Monroe Co., NY	
	Combustible Shredder to Loadout Building
Pipe Dia.	0.864 m (34 in.) Quantity: two pneumatic lines/processing line
Pipe Length	107 m (350 ft)
System Blower and Type	Centrifugal, negative pressure, air lock
Product	90% < 19 mm (3/4 in.)
Air Flow	16.5 m^3/s (35,000 CFM)
Solids Flow	20.9 Mg/h (23 TPH)
Fan Drive HP	93 kW (125 HP)
Solids-to-Air Ratio, SR, kg Solids/kg Air	0.29

5. Chicago, IL

	Plant to Storage	Storage to Boiler
Pipe Dia.	0.457 m (18 in.) Quantity: one	0.203 m (8 in.) Quantity: two
Pipe Length	305 m (1000 ft)	122 m (400 ft) and 107 m (350 ft)
System Blower and Type	Positive displacement, air lock	Positive displacement blower, air lock

5. Chicago, IL (cont'd.)

	Plant to Storage	Storage to Boiler
Product	38 mm (1.5 in.) RDF	38 mm (1.5 in.) RDF
Air Flow	5.67 m^3/s (12,000 CFM)	1.18 m^3/s (2500 CFM)
Solids Flow	72.6 Mg/h (80 TPH)	18.1 Mg/h (20 TPH) and 36.3 Mg/h (40 TPH)
Fan Drive	559 kW (750 HP), initial; 746 kW (1000 HP), modified	22 kW (30 HP)
Solids-to-Air Ratio, SR, kg Solids/kg Air	2.97	3.56 and 7.12

6. Milwaukee, WI

	Receiving to Storage	Storage to Boiler
Pipe Dia.	0.457 m (18 in.) Quantity: one	0.254 m (10 in.) Quantity: four
Pipe Length	55 m (180 ft)	152.4 to 274.3 m (500 to 900 ft)
System Blower and Type	Positive displacement blower, air lock	Positive displacement blower, air lock
Product	19 mm (3/4 in.) RDF	19 mm (3/4 in.) RDF
Air Flow	5.3 m^3/s (11,215 CFM)	1.6 m^3/s (3415 CFM/line)
Solids Flow	54.5 Mg/h (60 TPH)	9.1 Mg/h (10 TPH) per pipe
Fan Drive HP	186 kW (250 HP)	75 kW (100 HP)
Solids-to-Air Ratio, SR, kg Solids/kg Air	2.37	1.30

APPENDIX B

SAMPLE LETTER

To: Company XYZ

Re: Quote for Pneumatic Conveying Test Rig
(E.P.A. Contract)

Dear ... :

As agreed, I am sending to you, under same cover, a description and general performance specifications for a test pneumatic conveying rig, to be used on processed fractions from municipal solid waste (MSW). As you know from our previous discussions, our present contract with the Federal Government (U.S.E.P.A.) on "Conveyors for MSW" includes a section on pneumatic conveying.

As we discussed, I would appreciate, for budgetary purposes and to define future work as part of this investigation, your quote (price and list of equipment) for the rig described in the attachment. Other comments and suggestions would be welcome.

Also, I am interested to know how much you would charge (per day basis) for labor and materials on the assumption that the conveying tests would be performed at your site, using your existing facility. In this case, we would like you use the longest available circuit (not necessarily as long as 200 ft).

Your interest in our investigation of pneumatic conveying for MSW and your cooperation are appreciated. I am looking forward to your quote.

Sincerely yours,

Marc L. Renard, Ph.D.
Director of Research Programs

Enclosure

APPENDIX C

ALPHABETICAL LIST OF EQUIPMENT MANUFACTURERS CONTACTED DURING THIS INVESTIGATION

The list below does not claim to be inclusive. No endorsement is implied.

(1) CEA - Carter Day, Minneapolis, MN 55432 (Tel: 612/571-1000)

(2) Dry Bulk Engineers, Inc., 71 Hazel Lane, Piedmont, CA 94611 (Tel: 415/785-1391)

(3) NEU, S.A., Sac Postal 2028, F59013, Lille Cedex, France (Tel: 20-721700)

(4) Ohio Blow Pipe Co., 446 East 131st Street, Cleveland, OH 44108 (Tel: 216/681-7379)

(5) Quick Draft Corp., P.O. Box 1353, Station C, Canton, OH 44708 (Tel: 216/477-4574

(6) Rader Systems, Inc., 5350 Poplar Avenue, Suite 320, Memphis, TN 38117 (Tel: 901/761-3390)

(7) Sprout-Waldron, Div. of KOPPERS CO., Muncy, PA 17756 (Tel: 717/546-8211)

(8) Trimvac Systems, Konehansa Oy - Teollisuusmittaus Oy, Eerikinkatu 3A, 20110, Turku 11, Finland (Tel: 921-331557)

TEST FACILITIES VISITED

(1) NEU, S.A., Sac Postal 2028, F59013, Lille Cedex, France (Tel: 20-721700)

(2) Ohio Blow Pipe Co., 446 East 131st Street, Cleveland, OH 44108 (Tel: 216/681-7379)

(3) Sprout-Waldron, Div. of KOPPERS CO., Muncy, PA 17756 (Tel: 717/546-8211)